Frontiers of Rarity:
Searching for Unusual Kaon Decays at Fermilab

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Outline

- ▷ Frontiers in High Energy Physics
- ▷ The KTeV Experiments at Fermilab
- ▷ Themes in Rare Kaon Decays
- ▷ A Sampling of Rare Decay Results from KTeV
- ▷ CKM: The Future of Rare K Decay Physics at FNAL

Frontiers in High Energy Physics

- The Energy Frontier:
  - Basic Idea: excite new degrees of freedom directly
  - Technique: hurl extremely energetic particles at one another so that they annihilate
  - Advantage 1: permits direct determination of the spectrum
  - Advantage 2: data has extremely rich information content
  - Examples: J/Ψ; Υ; W/Z; t quark discoveries.
  - Disadvantage 1: $1/s$ cross sections require high luminosity
  - Disadvantage 2: extremely high cost, long timescale

Frontiers in High Energy Physics

- The Precision Frontier:
  - Basic Idea: new degrees of freedom are excited virtually
  - Technique: make extremely precise measurements that are sensitive to small shifts
  - Advantage 1: can sometimes detect couplings unmeasure-able in direct particle production
  - Advantage 2: can sometimes test subtle aspects of a theory, such as radiative corrections
  - Examples: LEP tests of Standard Model consistency; Brookhaven E821 measurement of a_μ; NA48 and KTeV measurements of Re(ϵ'/ϵ).

Frontiers in High Energy Physics

- The Precision Frontier:
  - Disadvantage 1: many SM and non-SM effects are combined in one measurement (an analogy is trying to learn about a painting by measuring its average color)
  - Disadvantage 2: a precise and well-understood theory is a critical prerequisite
  - Disadvantage 3: both experimental and theoretical systematic uncertainties can make results difficult or impossible to interpret.

Frontiers in High Energy Physics

- ## The Rarity Frontier:
  - Basic Idea: new degrees of freedom may break SM symmetries and conservation laws, so that forbidden or suppressed processes become allowed.
  - Technique: search for evidence of these processes, such as rare decays.
  - Advantage 1: precise predictions may not be essential to discovering new physics
  - Advantage 2: experimental signatures are often simple to define
  - Advantage 3: easy-to-understand statistical uncertainties are usually dominant

Frontiers in High Energy Physics

- ## The Rarity Frontier:

  - Examples: Absence of proton decay rules out many GUT's; Absence of $\mu \to e\gamma$ shows μ is not a simple excited electron; Absence of $K_L \to \mu e$ rules out some theories with horizontal gauge bosons or leptoquarks
  - Disadvantage 1: as with precision measurements, only one quantity is measured (per rare process), so competing non-SM theories may not be distinguishable.
  - Disadvantage 2: backgrounds can be hard to understand and are often difficult to suppress to the required level
  - Disadvantage 3: successful experiments generate null results, and this can be difficult to get excited about.

The KTeV Experiments

Two related experiments took data at FNAL in 1996-97 and again in 1999-2000:

- ▷ E832: A Precision Measurement of Re(ϵ'/ϵ)
- ▷ E799-II: A Search for Rare Decays of especially $K_L \to \pi^0 l\bar{l}$ modes.

E832: Precision Measurement of Re(ϵ'/ϵ)

- ▷ Experiment uses two parallel kaon beams
- ▷ An active regenerator makes K_S in one beam; the other is almost entirely K_L.
- ▷ All four $\pi\pi$ decays are detected simultaneously to promot cancellation of systematic uncertainties
- ▷ Acceptance differences are corrected using a precise Monte Carlo simulation
- ▷ Neutral kaon system parameters including ϵ' are extracted by fitting for the ratio of K_S to K_L decays as a function of momentum and vertex-z location.

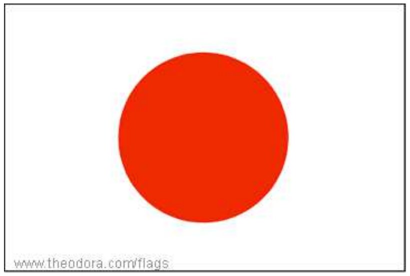
Final 1997 result: Re(ϵ'/ϵ) $= (20.7 \pm 1.5 \pm 2.4) \times 10^{-4}$

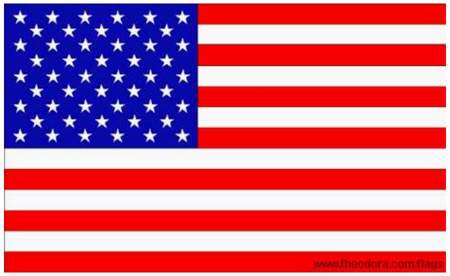
E799-II: Search for Rare Decays of the K_L

- ▷ Follow-up to E799-I, which ran in 1991 in M-Center
- ▷ E799-II still uses two parallel kaon beams
- ▷ The regenerator is removed, so both beams are mostly K_L
- ▷ The beam is made larger and more intense to maximize sensitivity at some cost to accidental backgrounds
- ▷ The magnetic field transverse kick is reduced to improve acceptance at some cost to resolution
- ▷ A system of transition radiation detectors is inserted in front of the EM calorimeter to improve particle identification, at some cost to CsI calorimeter precision
- ▷ A range of triggers is used to search for many rare K_L decays

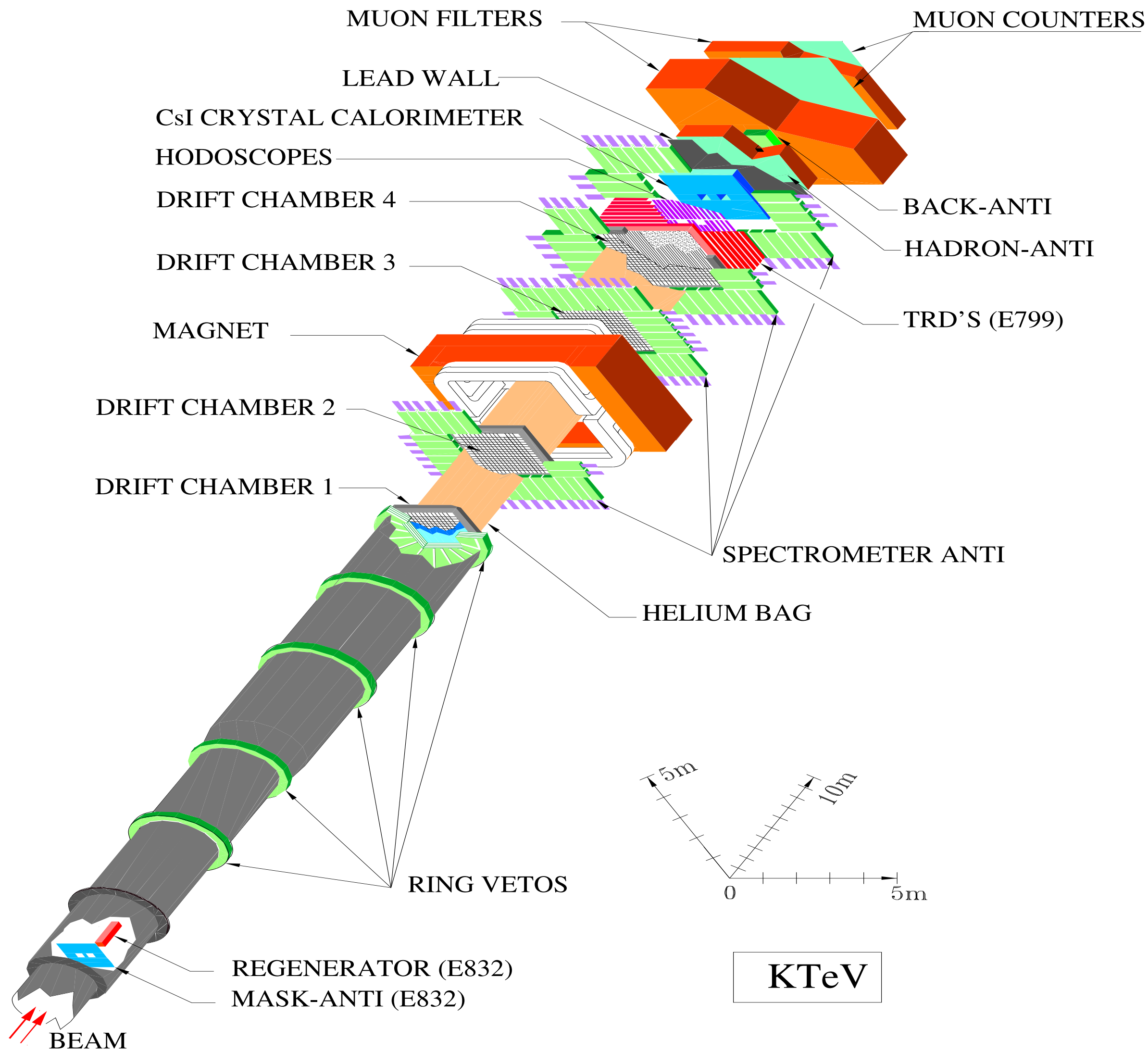
KTeV Collaborating Institutions in 2000

- Univ of Arizona
- Univ of California, Los Angeles
- Univ of California, San Diego
- Univ of Campinas, Brazil
- The University of Chicago
- Univ of Colorado, Boulder
- Elmhurst College
- Fermi National Accelerator Laboratory
- Osaka University, Japan
- Rice University
- Univ of Sao Paulo, Brazil
- Univ of Virginia
- Univ of Wisconsin, Madison



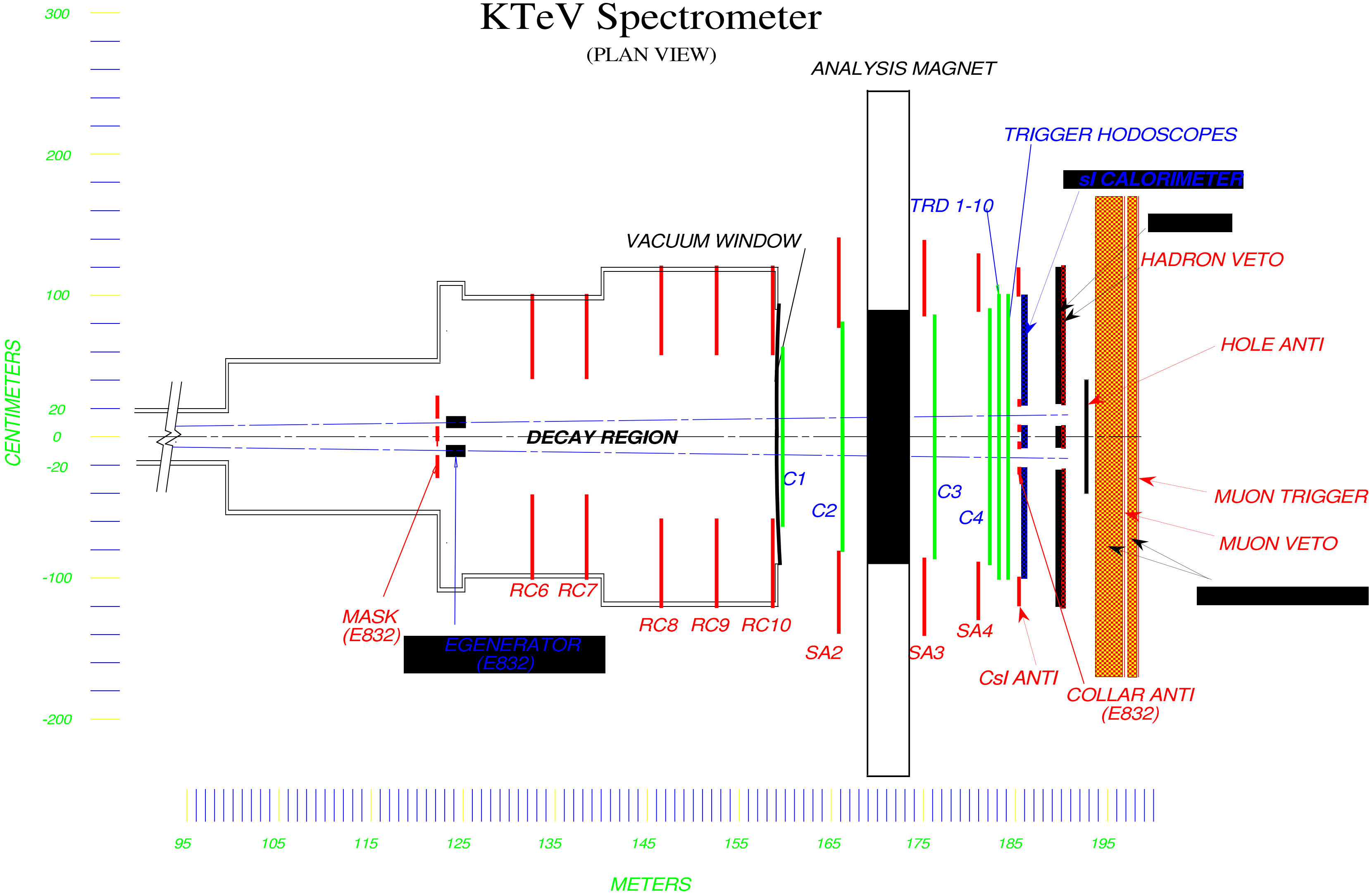


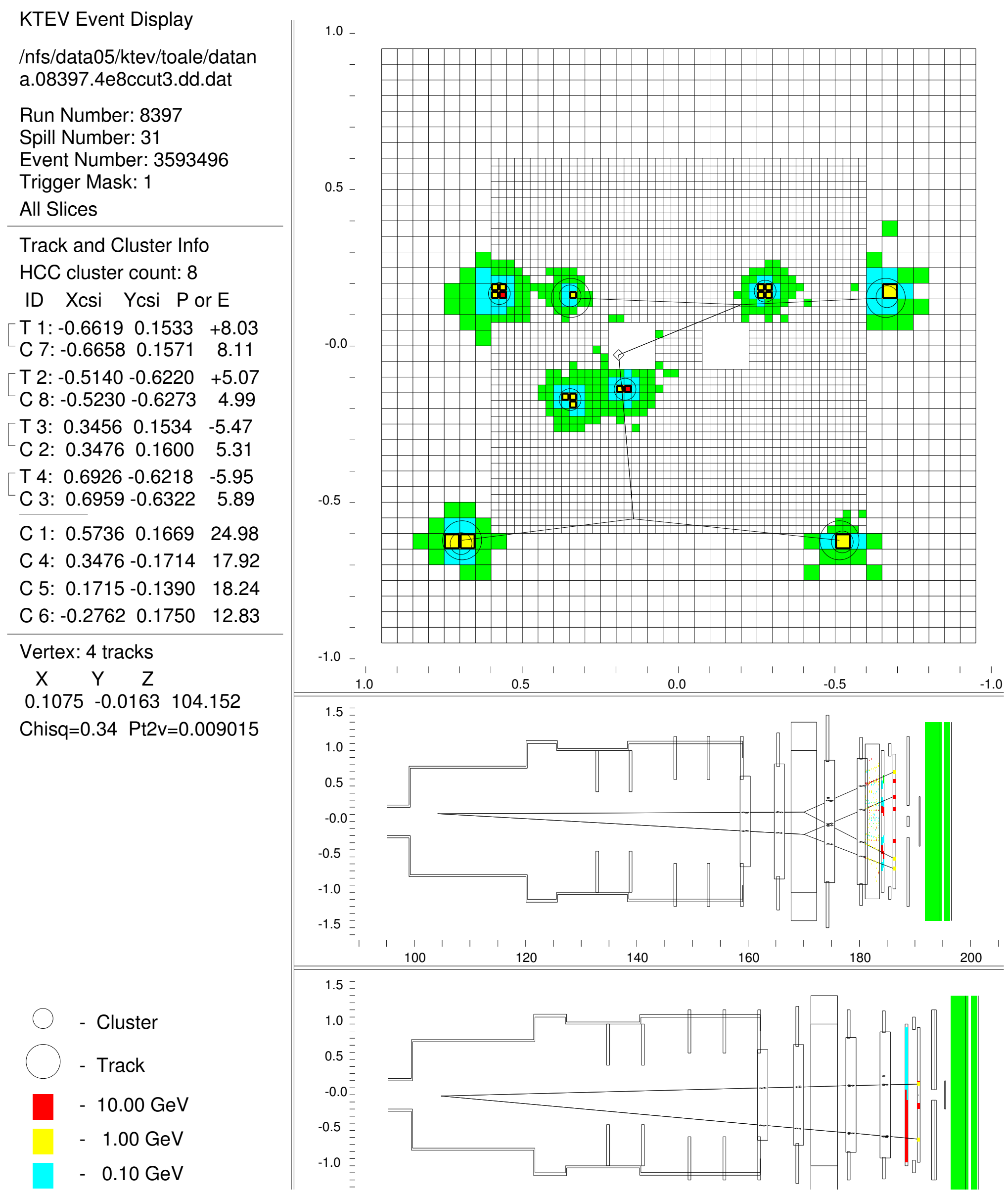
KTeV Spectrometer



KTeV Spectrometer

(PLAN VIEW)

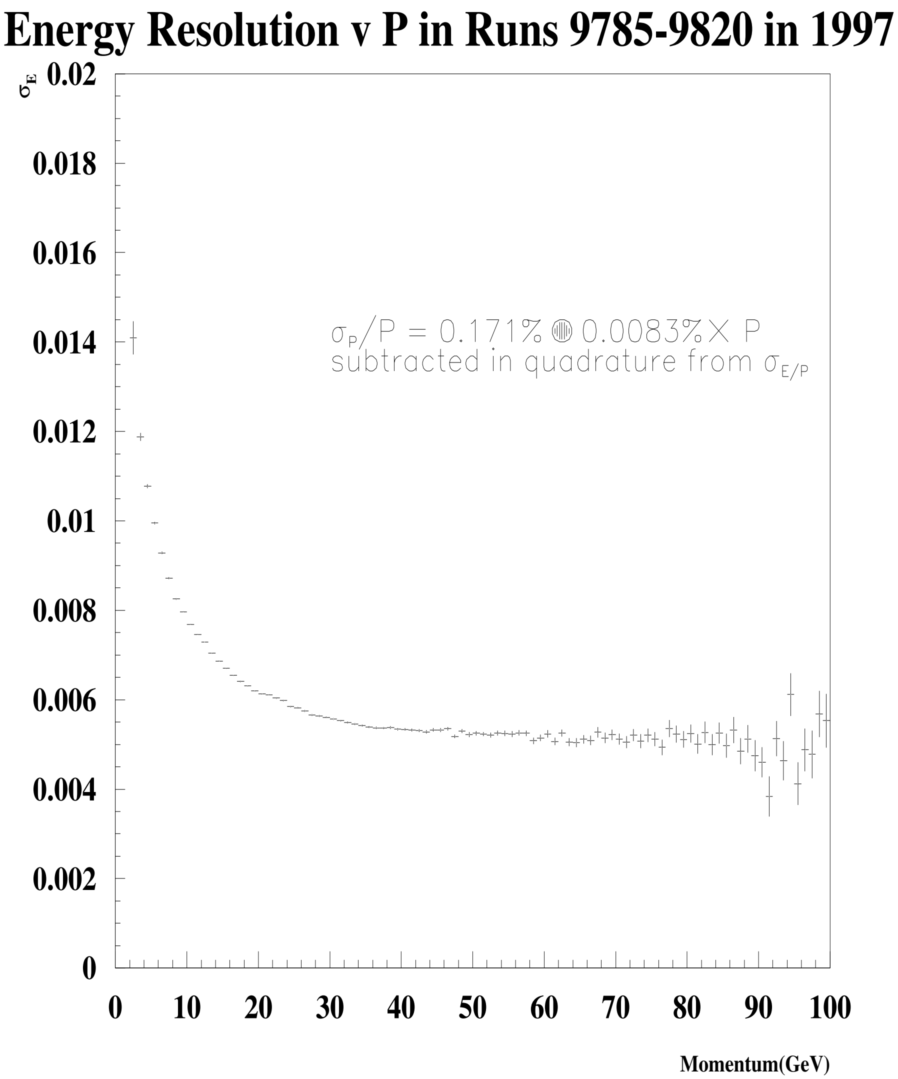




KTeV Detector

Event display for a $K_L \to \pi^0\pi^0\pi^0$ event with a $\pi^0 \to e^+e^-e^+e^-$ decay.

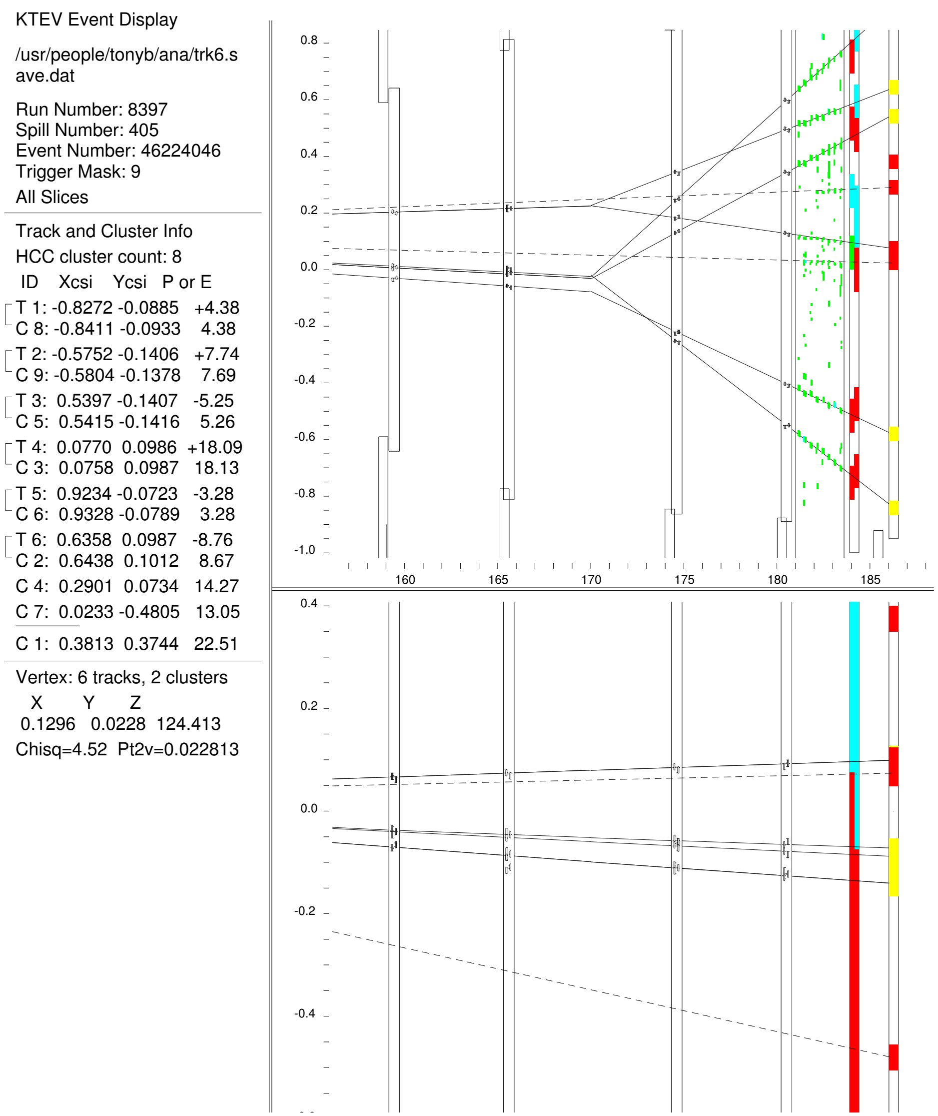
Views shown are CsI calorimeter beam's eye view, and charged spectrometer plan and elevation views.



KTeV Detector

Plot shows σ_E vs E based on observed E/p vs p distribution for electrons from K_{e3} events in E832.

The KTeV CsI calorimeter performance is important in analysing rare decays, because it allows us to make tight E/p cuts for particle identification and to used narrow mass windows for π^0 reconstruction.



KTeV Detector

Event display, showing activity in the TRD system for a $K_L \to \pi^0\pi^0\pi^0$ event with three π^0 Dalitz decays.

The TRD's can achieve 90% electron-identification efficiency with a less than 1% pion misidentification. This is important in reducing background from common K_{e3} decays combined with accidentals.

Themes in Rare Kaon Decays

- ▷ Bread-and-butter physics: semi-leptonic, radiative, and electromagnetic decays.
  These provide information on form factors, as well as tests of QED and chiral perturbation theory calculations.
  They are often important inputs to searches for more exotic or interesting modes.

- ▷ Standard Model physics: FCNC modes, or modes with important contributions from electromagnetic penguin operators.
  These include $K_L \to \mu^+\mu^-$, $K_L \to \pi^0 e^+ e^-$, and $K \to \pi\nu\bar{\nu}$.
  Measurements may be sensitive to CKM matrix parameters.

- ▷ Exotic physics: modes that are forbidden or almost forbidden in the Standard Model. These are principally $K_L \to \mu e$ and $K \to \pi\mu e$. Observation would signal physics beyond the Standard Model.

An example of one family of “Bread-and-Butter” Rare Kaon Decays: $K \to \pi\pi\gamma$ and Related Modes

- $K^+ \to \pi^+\pi^0\gamma$
  Test of Chiral perturbation theory for Direct-Emission (DE) component;
  Also has an important Inner-Bremsstrahlung (IB) contribution;
  Most recent measurement by BNL E787 (2000):

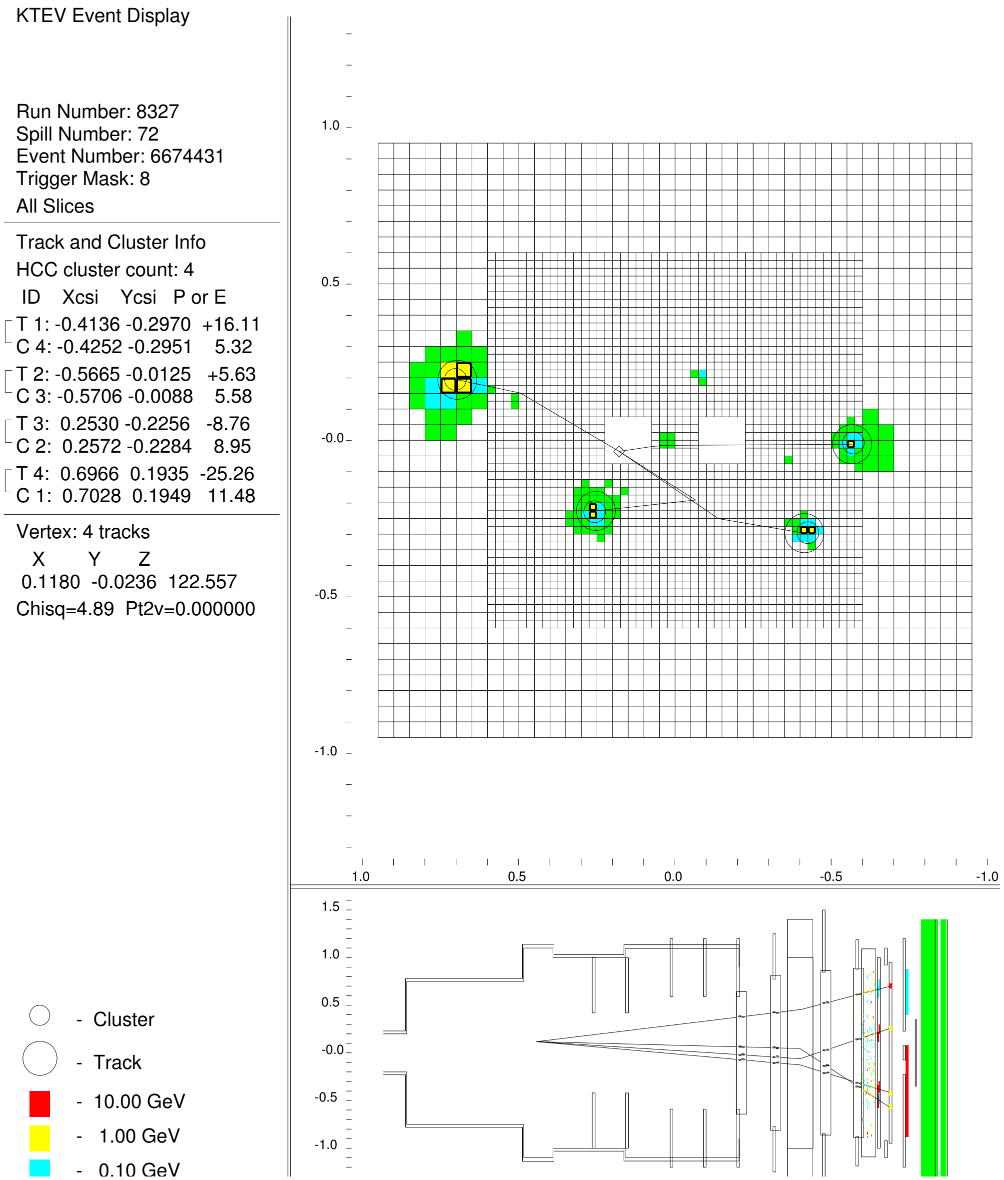
$$B(DE) = (4.72 \pm 0.77) \times 10^{-6}$$

- $K_L \to \pi^+\pi^-\gamma$
  Used to measure DE form factor;
  DE part comparable to IB, dominates for high E_γ;
  Most recent measurement by KTeV (2000):

$$B(DE) = (3.70 \pm 0.10) \times 10^{-5}$$

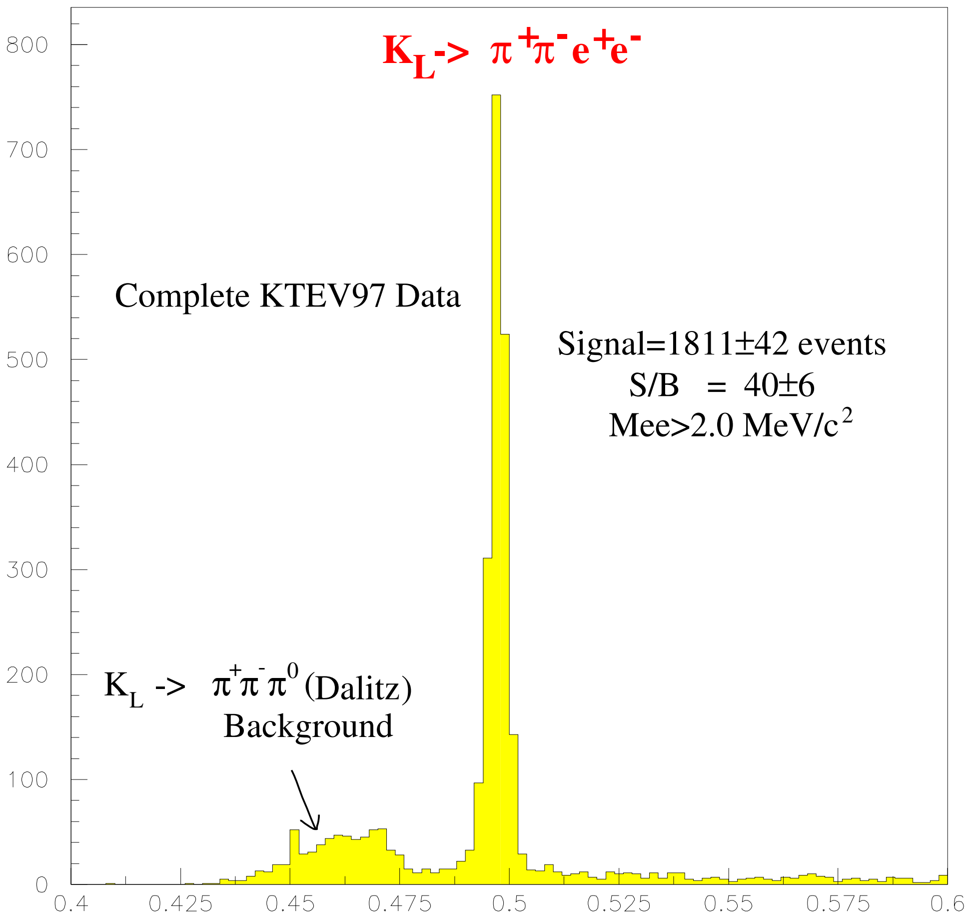
- $K_L \to \pi^+\pi^-e^+e^-$
  Interference between CP-conserving DE amplitude
  and indirect-CP-violating IB amplitude produces extremely large CP-odd and T-odd final-state angular distribution.
  Most recent measurement by KTeV (1999):

$$B(DE + IB) = (3.63 \pm 0.11 \pm 0.14) \times 10^{-7}$$



Event display for a $K_L \to \pi^+\pi^-e^+e^-$ event

Note the low E/p values for the two charged pions, and the typically close tracks of the e^+e^- pair.



Total invariant mass plot for $\pi^+\pi^-e^+e^-$ candidate events.

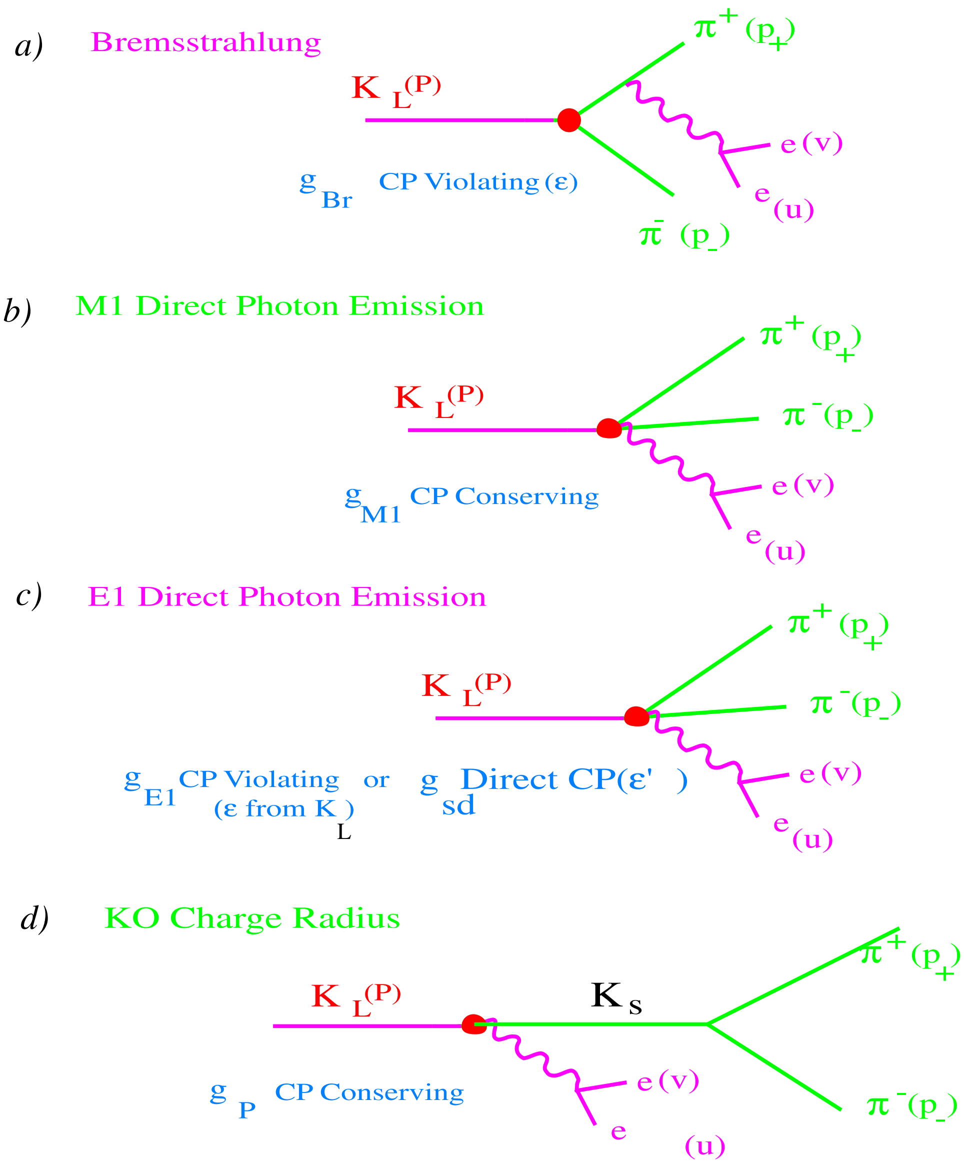
KTeV published the first observation and branching ratio measurement for this decay in 1998.

From the full 1997 E799 dataset, the reported branching ratio is

$$B(K_L \to \pi^+\pi^-e^+e^-) =$$

$$(3.63 \pm 0.11 \pm 0.14) \times 10^{-7}.$$

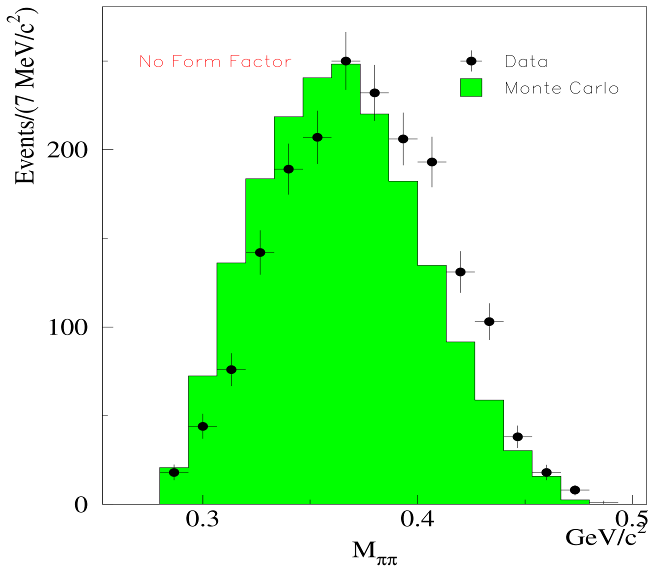
The Physics of K->ππee

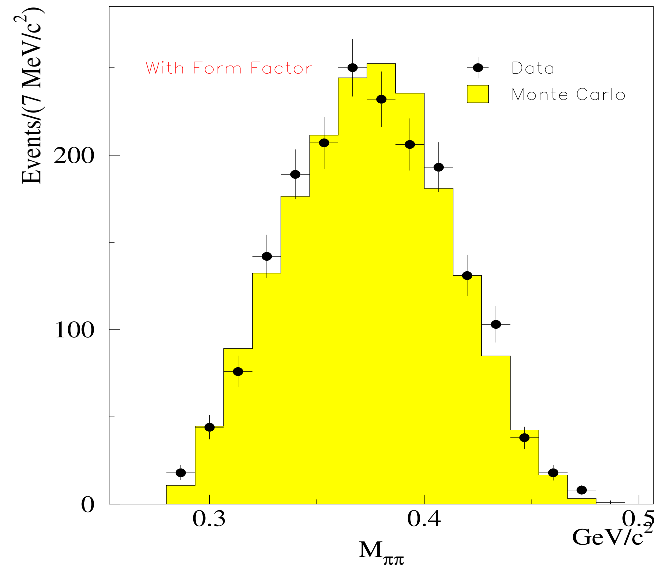


Amplitudes contributing to the decay $K_L \to \pi^+\pi^-e^+e^-$.

The first one shown here is CP-Violating; the second is CP-Conserving. These two amplitudes dominate the total, and their interference generates a CP-Violating angular asymmetry.

Determination of M1 Form Factor for $K_L \to \pi^+\pi^-e^+e^-$





The M1 direct emission amplitude requires a form factor, a fact known from previous measurements of $K_L \to \pi^+\pi^-\gamma$.

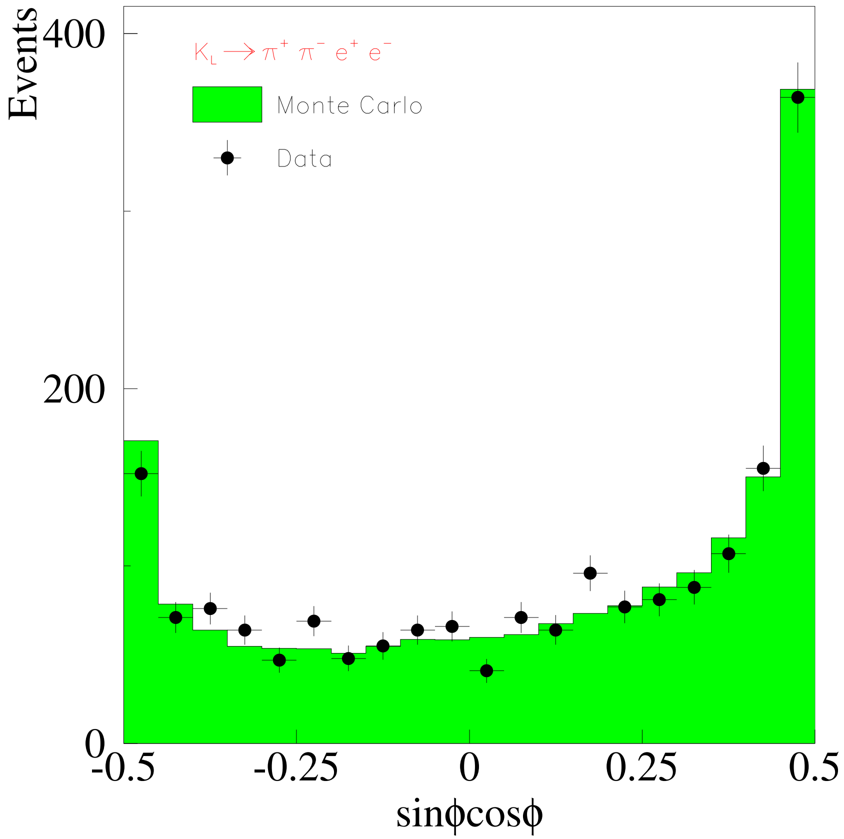
We have performed a maximum likelihood fit for the form factor

$$F_{M1}(M_{\pi\pi}^2) = \tilde{g}_{M1}\left[1 + \frac{a1/a2}{(M_\rho^2 - M_K)^2 + 2M_K E_{ee}}\right]$$

with the results

$\tilde{g}_{M1} = 1.35^{+0.20}_{-0.17} \pm 0.04$ $\qquad$ $a1/a2 = -0.720 \pm 0.028 \pm 0.009\,\mathrm{GeV}^2$

Angular Asymmetry in $K_L \to \pi^+\pi^-e^+e^-$



Distribution of $\sin\phi\cos\phi$ for observed $K_L \to \pi^+\pi^-e^+e^-$ events. Phi is the angle between the $\pi^+\pi^-$ and e^+e^- planes in the K_L CM.

The raw (not corrected for acceptance) angular asymmetry $\mathcal{A}_\phi$ is

$$\frac{N(\sin\phi\cos\phi > 0) - N(\sin\phi\cos\phi < 0)}{N(\sin\phi\cos\phi > 0) + N(\sin\phi\cos\phi < 0)} = 23.3 \pm 2.3\%.$$

Why is a ϕ Asymmetry CP-Violating and T-Odd?

- The ϕ Asymmetry indicates the presence of a term proportional to $\sin\phi\cos\phi$ in the differential partial width for the decay:

$$\frac{d\Gamma(\pi^+\pi^-e^+e^-)}{d\phi} = \Gamma_0 + \Gamma_1\cos^2\phi + \Gamma_2\sin\phi\cos\phi.$$

- Let the four vectors of the final state particles be p_+, p_-, q_+, and q_- for the π^+, π^-, e^+, and e^-, respectively. Then the C, P, T-symmetries of $\sin\phi\cos\phi$ are the same as those of the Lorentz invariant

$$\epsilon_{\alpha\beta\gamma\delta}\, p_+^\alpha\, p_-^\beta\, q_+^\gamma\, q_-^\delta$$

- Under C, the $+$ and $-$ four vectors are exchanged, with no change in this quantity.

- Under P or T, the spatial components of the four-vectors flip sign, but the temporal components don't. Since the Levi-Civita tensor selects one temporal and three spatial components, the invariant above is odd under T, and also under CP as well as P.

Measurement of the CP-Violating Angular Asymmetry in $K_L \to \pi^+\pi^-e^+e^-$

The raw asymmetry of $23.3 \pm 2.3\%$, is amplified by the detector acceptance, because the acceptance is greater in regions of phase space where the real asymmetry is large.

We have determined the integrated, acceptance-corrected asymmetry by using a Monte Carlo simulation based on a paper by Sehgal and Wanninger (*Phys. Rev.* **D46,** 1035 (1992) and *ibid* **D46,** 5209(E).)

The matrix element in this paper is modified by the addition of the fitted M1 form factor, and the resulting corrected asymmetry is found to be

$$\mathcal{A}_{corrected} = 13.6 \pm 2.5 \pm 1.2\%,$$

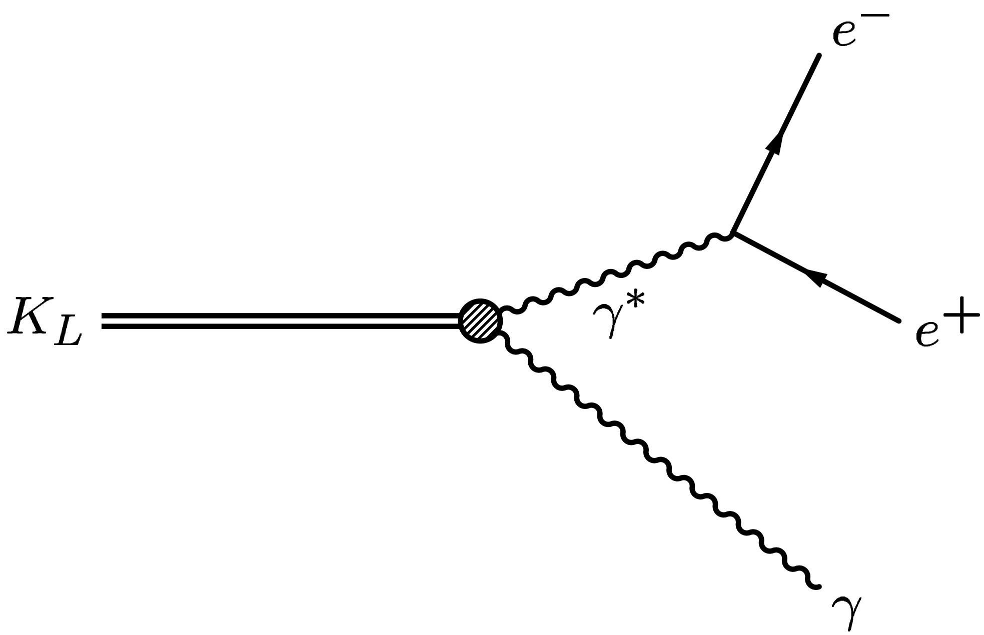
in very good agreement with the theoretical prediction for the integrated asymmetry.

Another family of “Bread-and-Butter” Rare K Decays

- Electromagnetic Modes
  - $K_L \to \gamma\gamma$
  - Dalitz Decays: $K_L \to e^+e^-\gamma$ and $K_L \to \mu^+\mu^-\gamma$
  - Double Dalitz Decays: $K_L \to e^+e^-e^+e^-$, $K_L \to e^+e^-\mu^+\mu^-$, and $\to \mu^+\mu^-\mu^+\mu^-$
  - Radiative Dalitz Decays $K_L \to e^+e^-\gamma\gamma$ and $K_L \to \mu^+\mu^-\gamma\gamma$.
- $K \to \gamma\gamma$ can be calculated in chiral perturbation theory.
- The Dalitz and Double Dalitz modes can provide information on the $K_L\gamma\gamma$ form factor which is vital to extracting interesting physics from measurements of $K_L \to \mu^+\mu^-$.
- The radiative Dalitz modes are the dominant backgrounds to measurements of $K_L \to \pi^0 e^+e^-$ and $K_L \to \pi^0\mu^+\mu^-$.

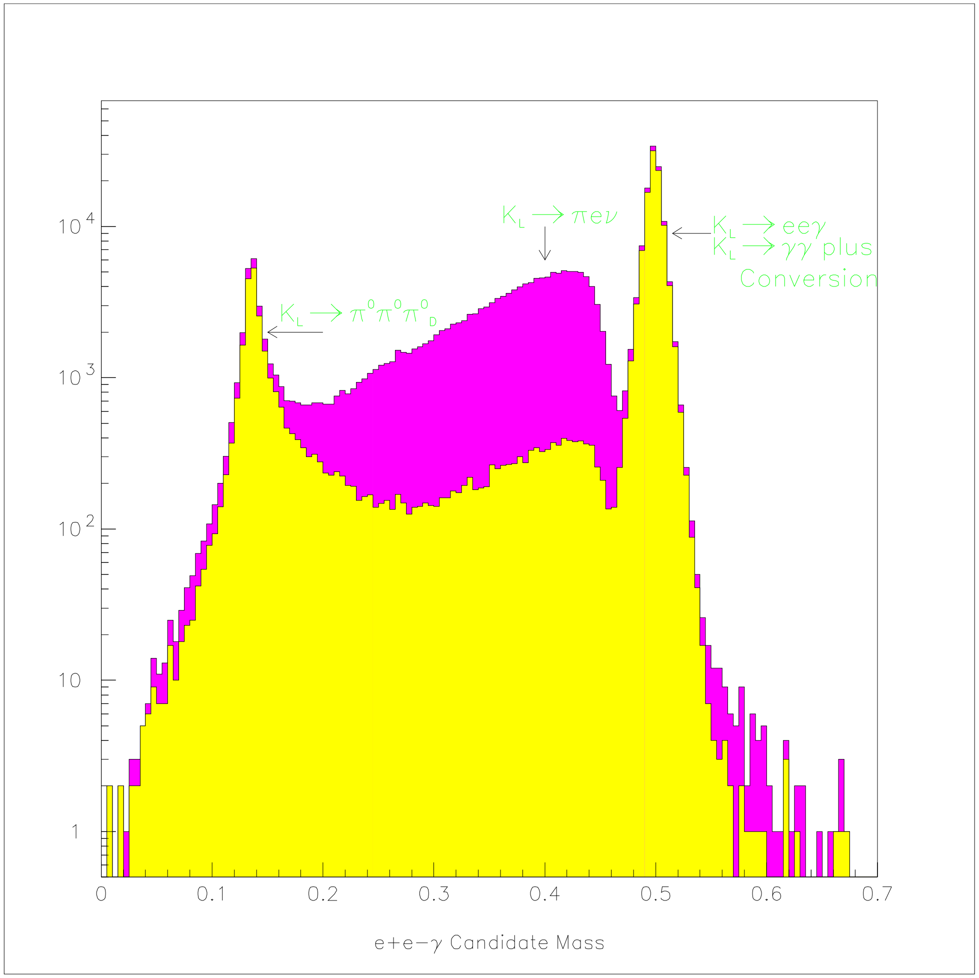
Measurements of $K_L \to e^+e^-\gamma$

The decay $K_L \to e^+e^-\gamma$ proceeds via $K_L \to \gamma^*\gamma$, where the virtual photon converts internally into an e^+e^- pair:



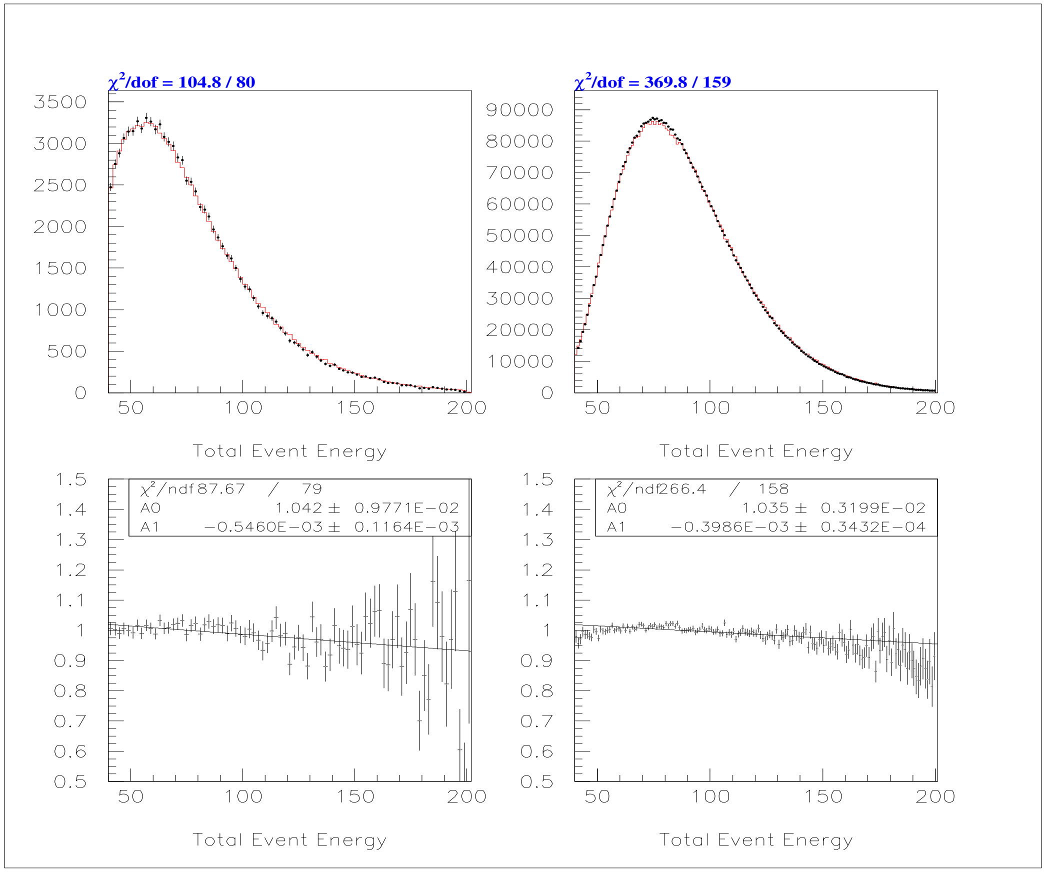
The functional dependence of the $K_L\gamma\gamma^*$ coupling on the q^2 of the virtual photon is called the $K_L\gamma\gamma$ form factor. It can be determined from the observed M_{ee} spectrum.

Measurement of $K_L \to e^+e^-\gamma$



- ▷ TRD particle identification is used to reject backgrounds involving misidentified charged pions.
- ▷ A cut requiring track separation of 1.5 mm rejects essentially all external conversion backgrounds.
- ▷ In the 1997 data, KTeV has identified 93,383 $K_L \to e^+e^-\gamma$ candidate events, over a background estimated to be less than 0.1% after these cuts.

Measurement of $K_L \to e^+e^-\gamma$



Total Energy of Event

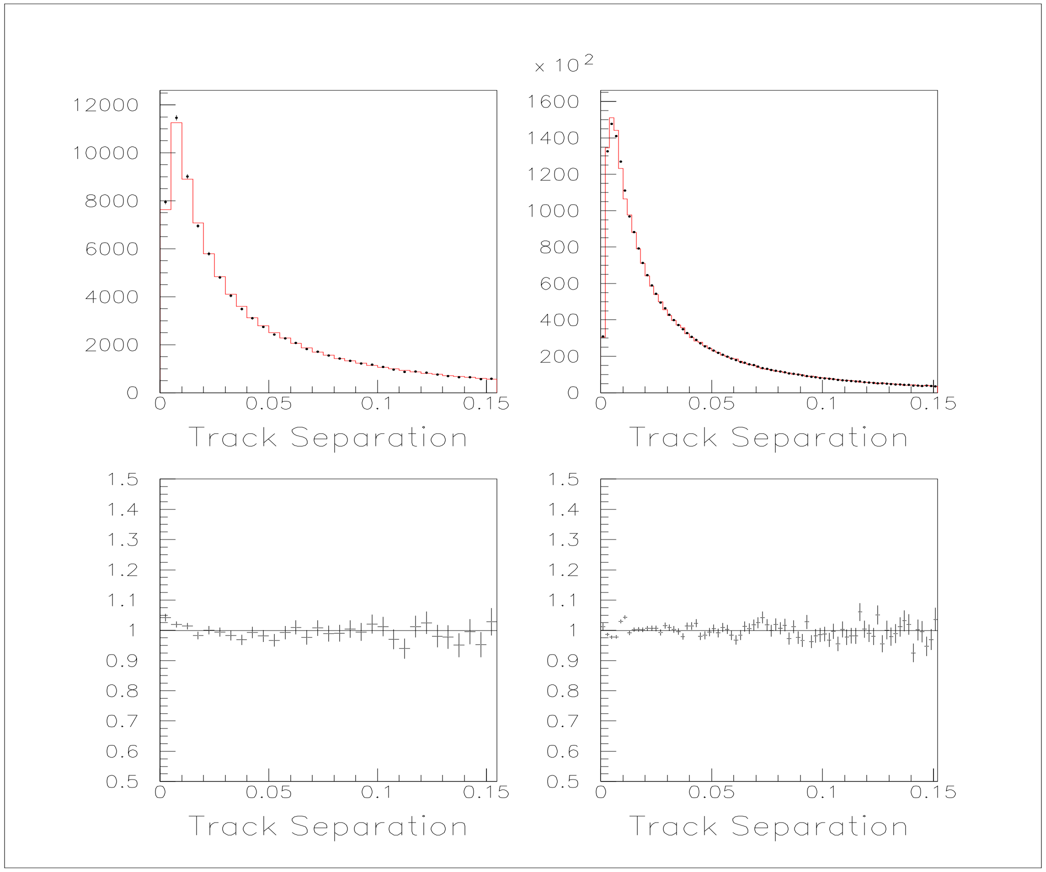
Left is Signal

($K_L \to e^+e^-\gamma$)

Right is Normalization

($K_L \to \pi^0\pi^0\pi^0_D$)

Measurement of $K_L \to e^+e^-\gamma$



Track Separation at Chamber 1

Left is Signal

($K_L \to e^+e^-\gamma$)

Right is Normalization

($K_L \to \pi^0\pi^0\pi^0_D$)

Preliminary $K_L \to e^+e^-\gamma$ Branching Ratio

Best previous published result, from CERN/NA48

$BR(K_L \to e^+e^-\gamma) = [10.6 \pm 0.2(\text{stat}) \pm 0.2(\text{sys}) \pm 0.4(\text{extsys})] \times 10^{-6}$

$K_L \to e^+e^-\gamma$ events observed (N_{Sig}): 93383

$K_L \to \pi^0\pi^0\pi^0_D$ events observed (N_{Norm}): 5306073

$K_L \to e^+e^-\gamma$ Acceptance (ϵ_{Sig}): 0.03422(4)

$K_L \to \pi^0\pi^0\pi^0_D$ Acceptance (ϵ_{Norm}): 0.00266(2)

$$\frac{BR(K_L \to e^+e^-\gamma)}{BR(K_L \to \pi^0\pi^0\pi^0_D)} = \frac{N_{Sig}}{N_{Norm}} \cdot \frac{\epsilon_{Norm}}{\epsilon_{Sig}}$$

Flux: $(2.69 \pm 0.08) \times 10^{11}$

$BR(K_L \to e^+e^-\gamma) = [10.19 \pm 0.04(\text{stat})] \times 10^{-6}$

$K_L \rightarrow e^+e^-\gamma$ Branching Ratio

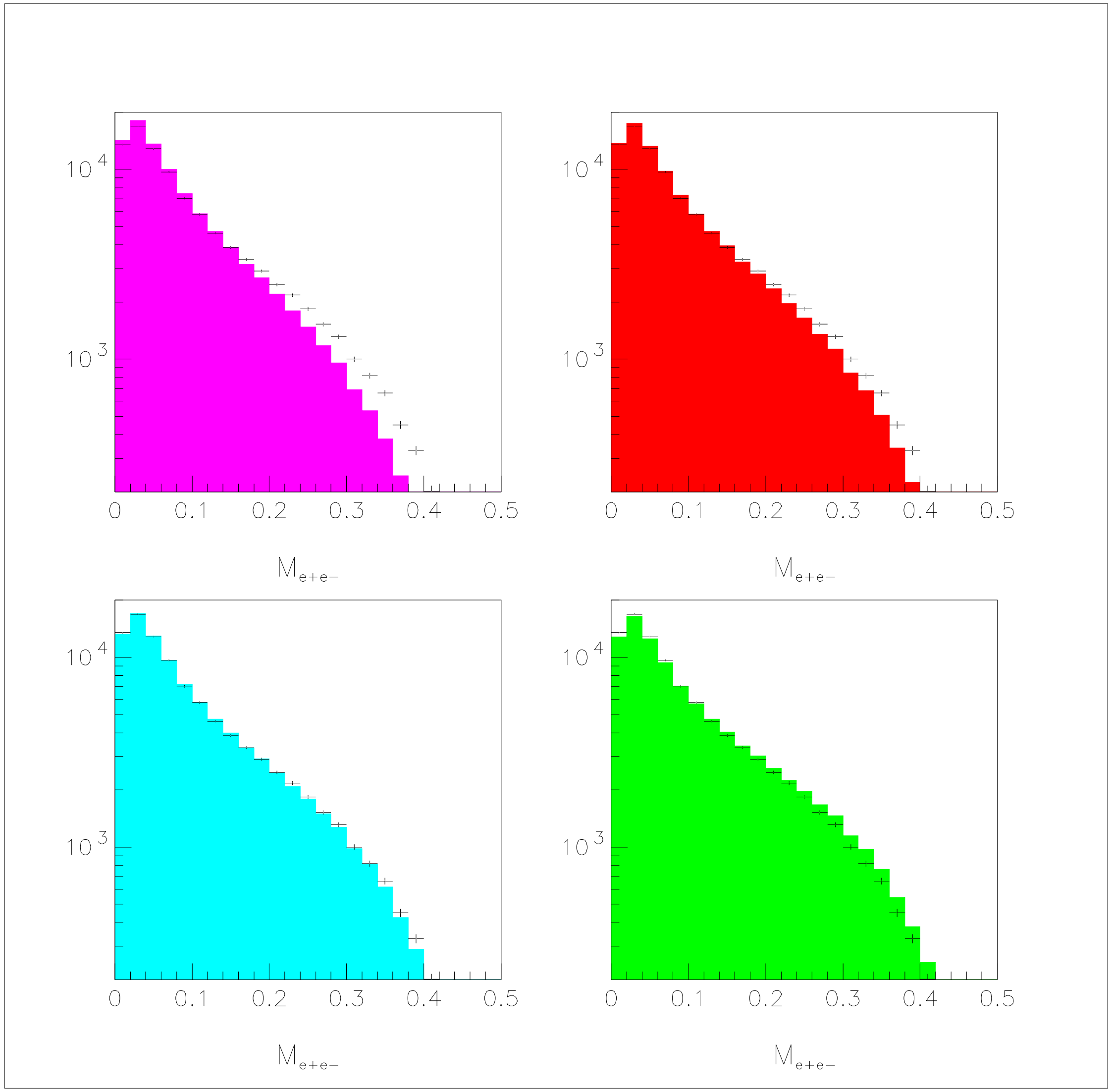
Contributions to overall uncertainty

Statistical Uncertainty	0.36%
Internal Systematic Uncertainty	
Absolute Photon Inefficiency	0.43%
Drift Chamber Inefficiencies	0.37%
Vary Cuts	0.33%
Energy Slope	0.23%
Energy Resolution	0.14%
Background	0.08%
Upstream Material	0.07%
Track Position Resolution	0.04%
Form Factor Uncertainty	0.03%
$\mathcal{O}(\alpha^3)$ Radiative Corrections	0.03%
Total Internal Systematic	0.72%
External Systematic Uncertainty	2.85%

External systematic is mostly from uncertainty in the $\pi^0 \rightarrow e + e^-\gamma$ branching fraction. Can KTeV improve this?

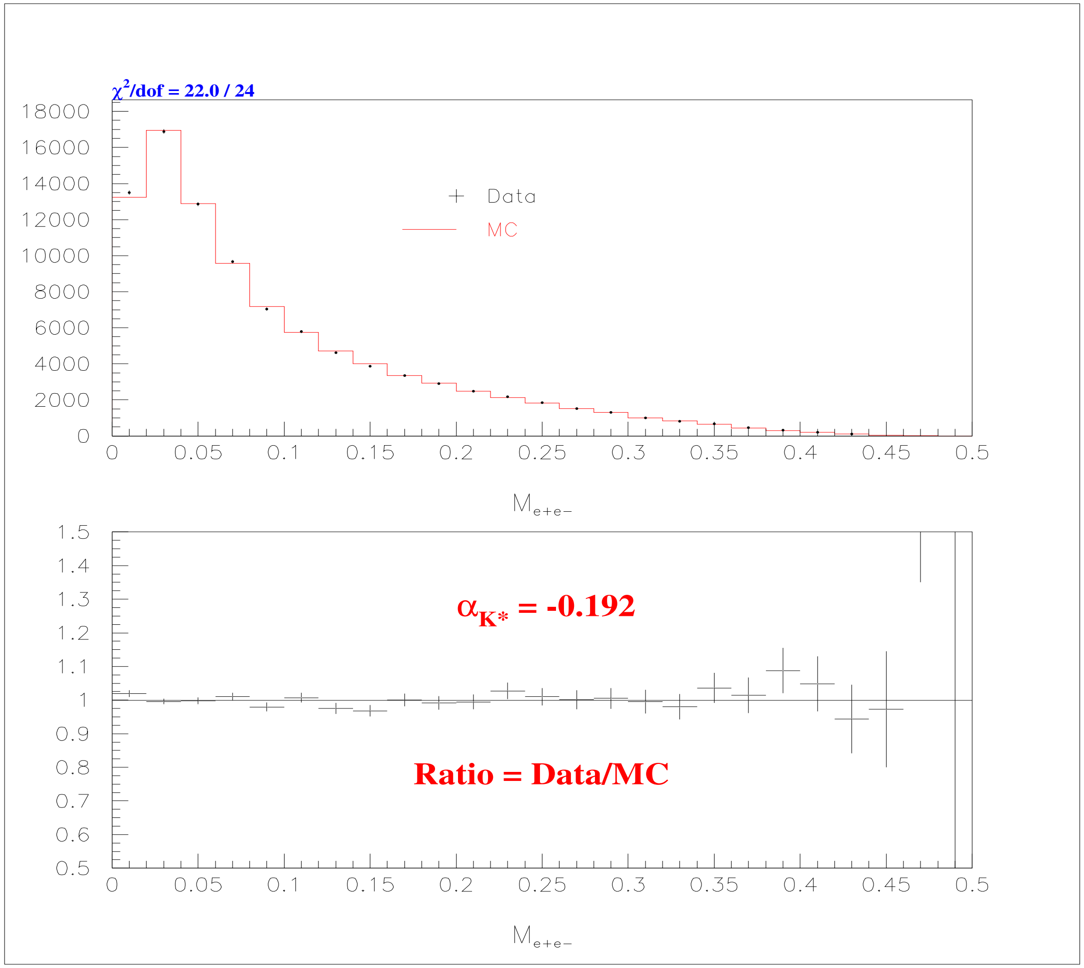
$$B(K_L \rightarrow e^+e^-\gamma) =$$
$$[10.19 \pm 0.04(\text{stat}) \pm 0.07(\text{sys}) \pm 0.29(\text{ext sys})] \times 10^{-6}$$

$K_L \to e^+e^-\gamma$ Form Factor



Plots showing the mass of the e^+e^- system, which is sensitive to the BMS form factor parameter α_{K^*}. Crosses are the the data, the histograms are MC with $\alpha_{K^*} = +0.20, +0.00, -0.16, -0.36$.

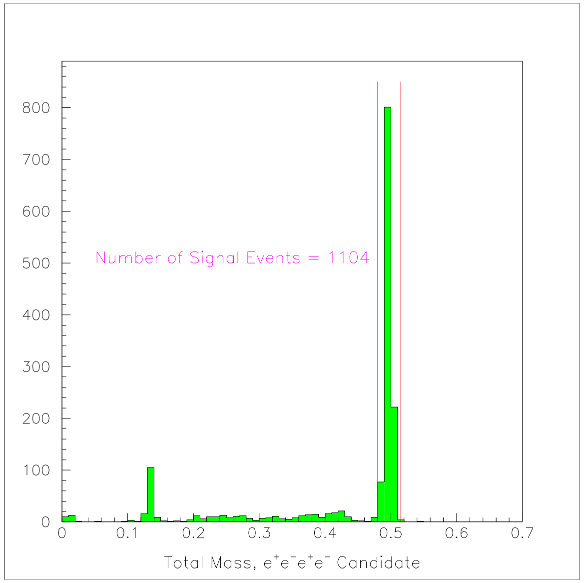
$K_L \to e^+e^-\gamma$ Form Factor



The mass of the e^+e^- system, histogram is the Monte Carlo with the best fit α_{K^*} and dots are the data. The ratio of the two is shown second.

The form factor result is $\alpha_{K^*} = -0.186 \pm 0.011 \pm 0.009$

Measurement of $K_L \to e^+e^-e^+e^-$



- We have published an analysis of the 441 $K_L \to e^+e^-e^+e^-$ events observed in the 1997 KTeV data. We determined

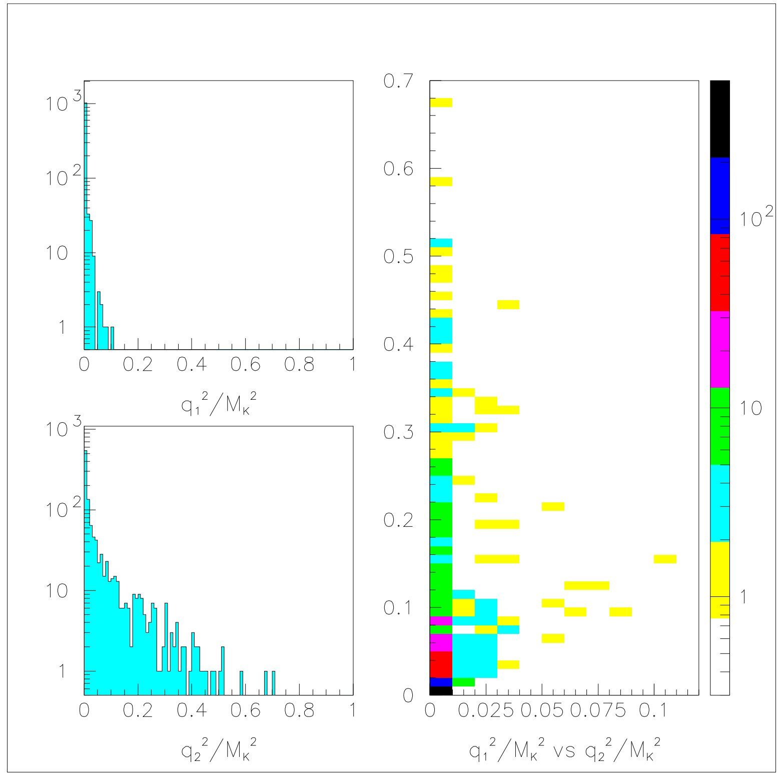
$$BR(K_L \to e^+e^-e^+e^-) = (3.72 \pm 0.18 \pm 0.23) \times 10^{-8}$$

- In the full KTeV dataset, we have identified 1056 examples of this decay, with negligible background. Preliminary Analysis of these data is now complete, with the result

$$BR(K_L \to e^+e^-e^+e^-) = (4.16 \pm 0.13 \pm 0.13 \pm 0.17) \times 10^{-8}$$

Measurement of

$K_L \to e^+e^-e^+e^-$

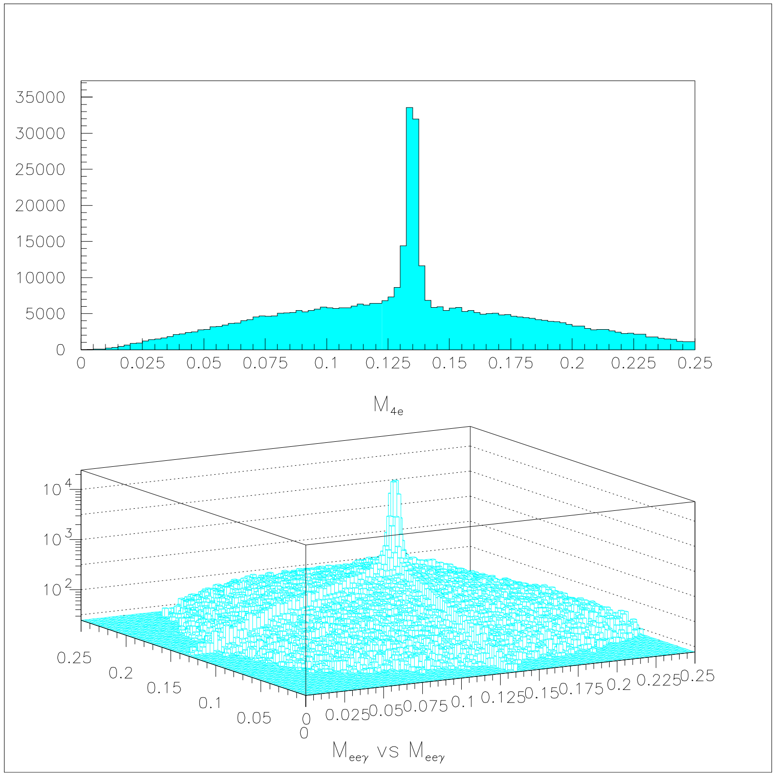


▷ We have extracted the $K_L\gamma^*\gamma^*$ form factor from the M_{ee} distributions for this sample of kaon double Dalitz decays, and find a preliminary value of

$$\alpha_{K^*} = -0.03 \pm 0.13 \pm 0.04,$$

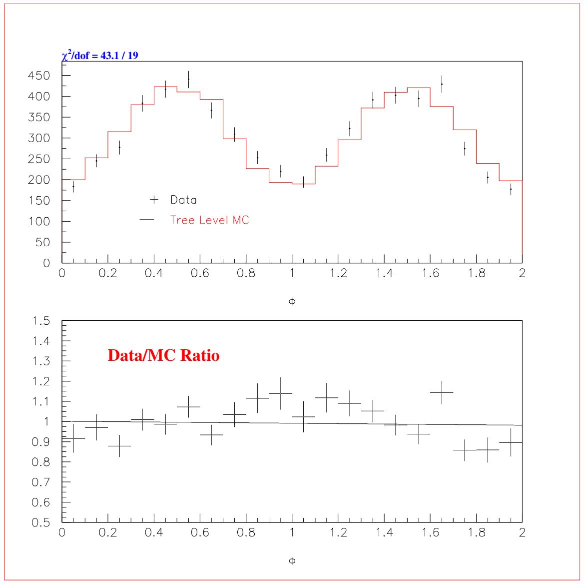
consistent with the single Dalitz result.

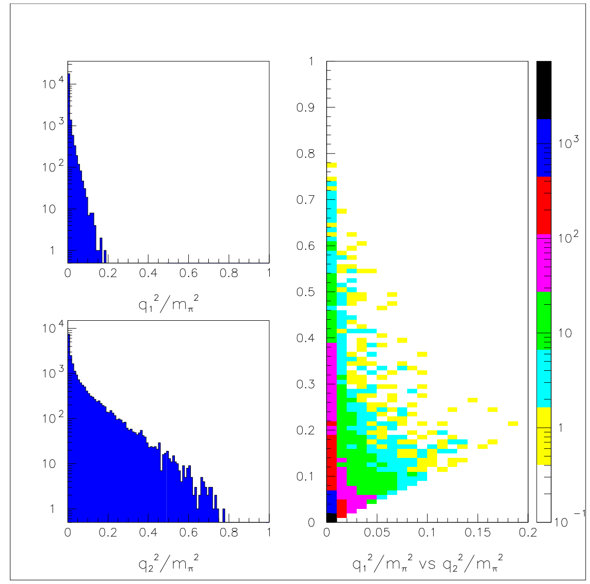
Measurement of $\pi^0 \to e^+e^-e^+e^-$



- ▷ In a sample of $e^+e^-e^+e^-\gamma\gamma\gamma\gamma$ events, we find both $K_L \to \pi^0\pi^0\pi^0$ with one $\pi^0 \to e^+e^-e^+e^-$ and with two $\pi^0 \to e^+e^-\gamma$ decays.
- ▷ These are separated using a kinematic χ^2, and conversions are eliminated with a track-separation cut.
- ▷ We find 27,954 $\pi^0 \to e^+e^-e^+e^-$ decays and normalize them to the sample of 132,086 double-$\pi^0 \to e^+e^-\gamma$ events.

Measurement of $\pi^0 \to e^+e^-e^+e^-$





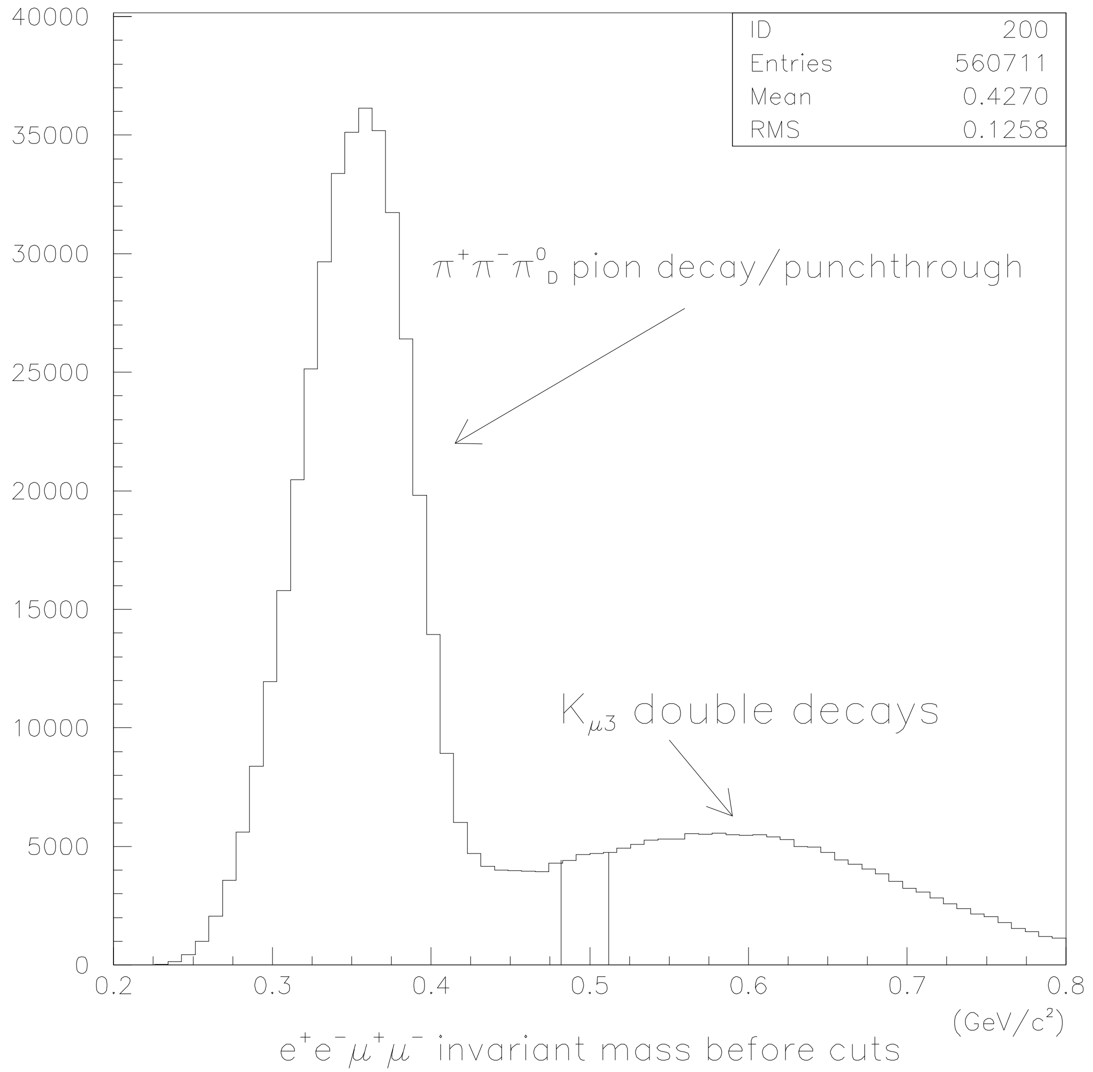
The result is

$$\frac{BR(\pi^0 \to e^+e^-e^+e^-)}{BR(\pi^0 \to e^+e^-\gamma)^2} = 0.2252 \pm 0.0015 \pm 0.0059$$

which implies

$$\frac{BR(\pi^0 \to e^+e^-e^+e^-)}{BR(\pi^0 \to \gamma\gamma)} = (3.274 \pm 0.022 \pm 0.197) \times 10^{-5}$$

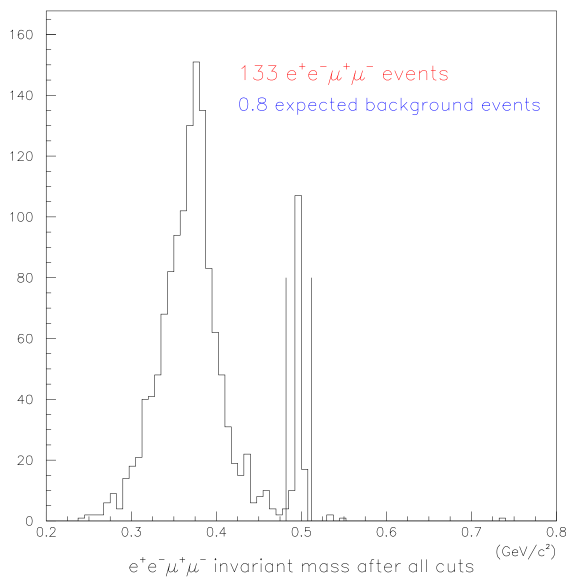
Measurement of $K_L \to e^+e^-\mu^+\mu^-$

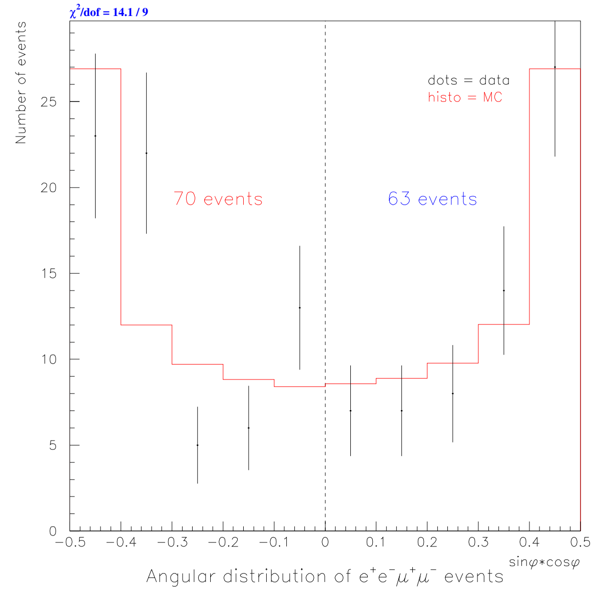


The backgrounds to the this mode are mostly from $K_L \to \pi^+\pi^-\pi^0$ and double (simultaneous) semileptonic decays.

The backgrounds are largely eliminated by cutting on $P_\perp^2$ and rejecting events with extra clusters in the CsI or poor vertex-reconstruction quality.

Measurement of $K_L \to e^+e^-\mu^+\mu^-$





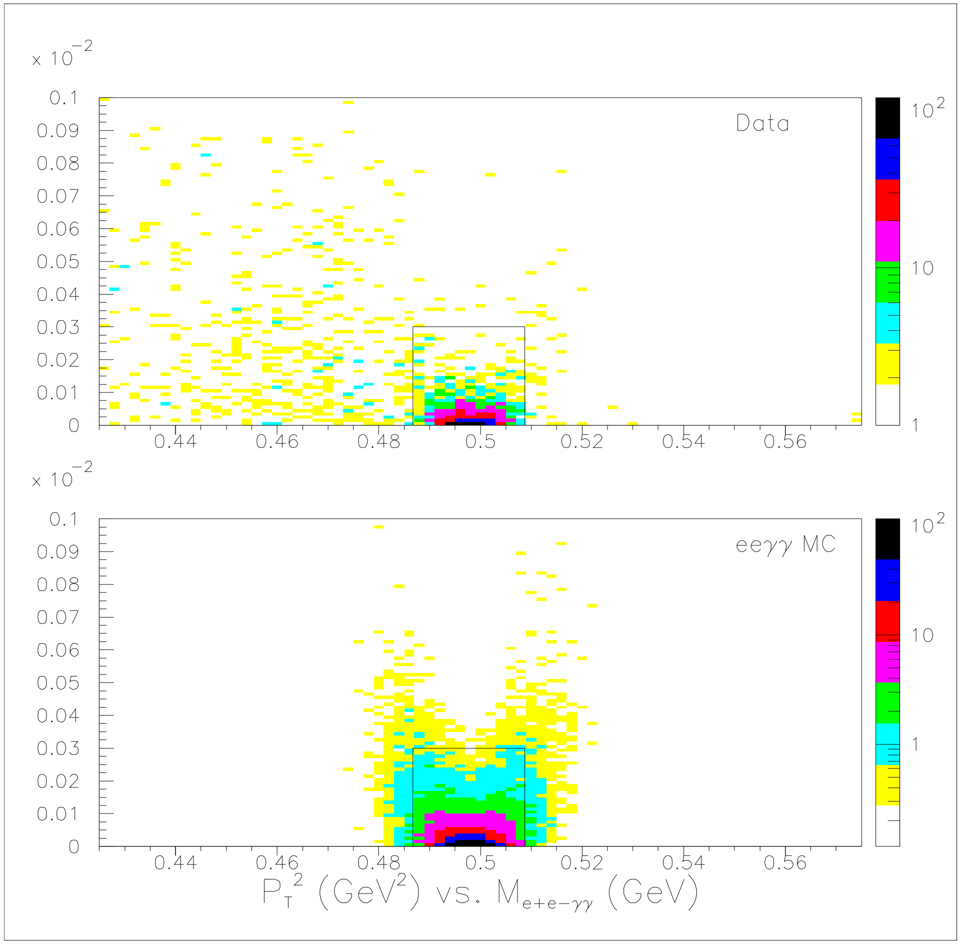
A total of 133 candidate events remain after all cuts, with a background estimated at 0.82 events.

The branching fraction is measured to be

$$BR(K_L \to e^+e^-\mu^+\mu^-) = (2.69 \pm 0.24 \pm 0.12) \times 10^{-9}$$

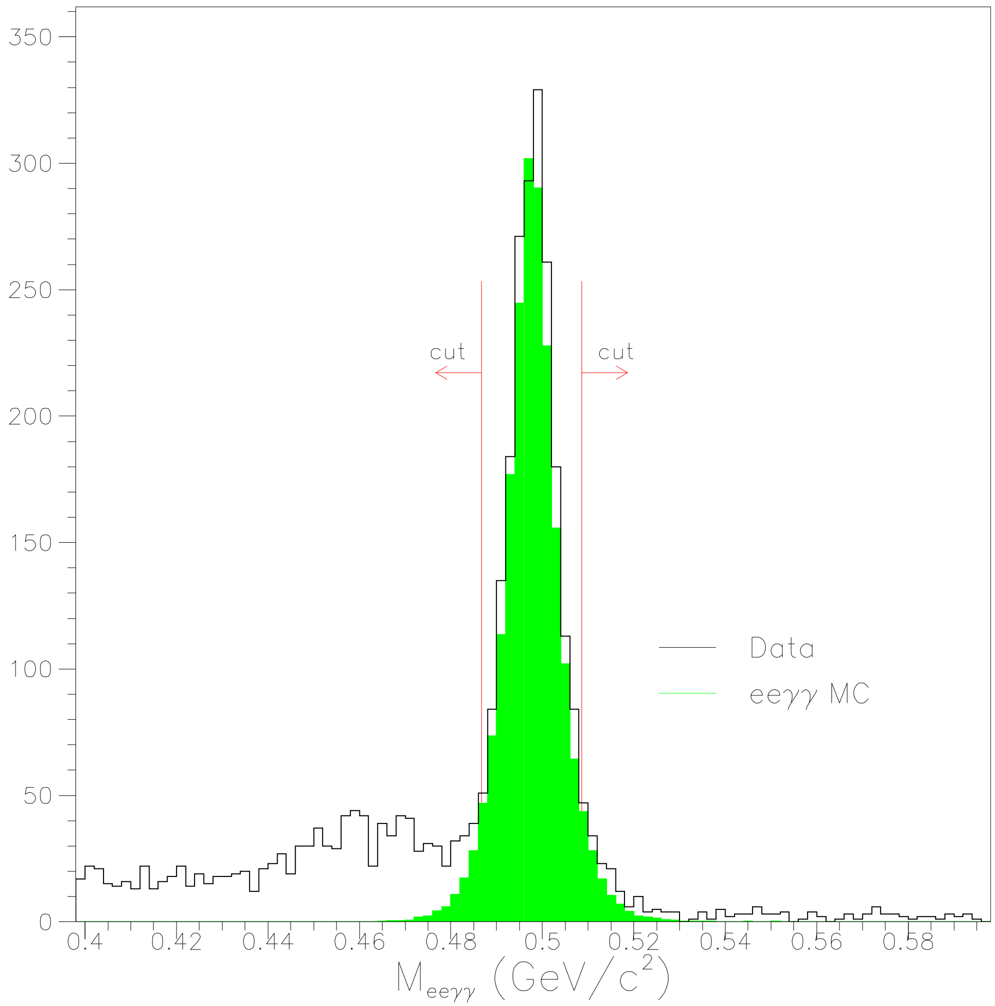
No CP-violating asymmetry is seen in the distribution of $\sin\phi\cos\phi$, where ϕ is the angle between the e^+e^- and $\mu^+\mu^-$ planes in the kaon rest frame.

Measurement of $K_L \to e^+e^-\gamma\gamma$



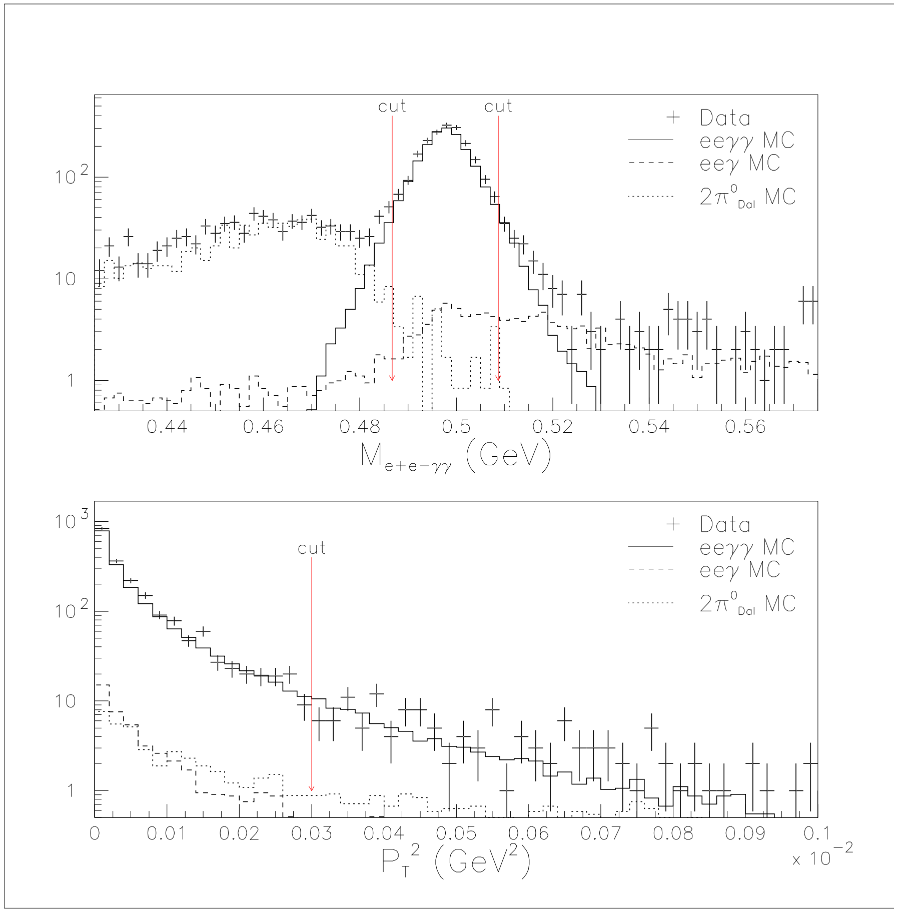
Transverse momentum-squared in GeV$^2/c^2$ vs. Invariant Mass of $e^+e^-\gamma\gamma$ system in GeV$/c^2$.

Measurement of $K_L \to e^+e^-\gamma\gamma$



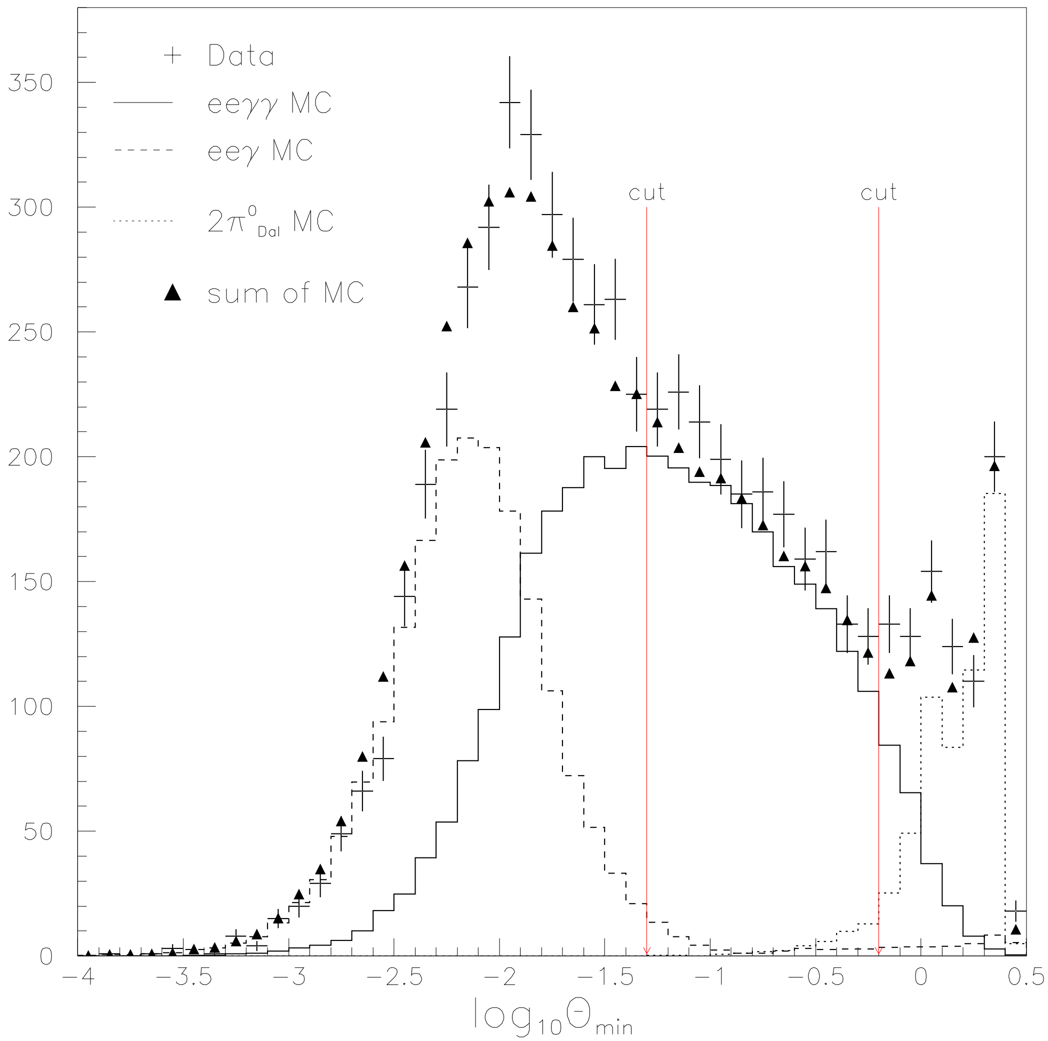
Invariant mass of $e^+e^-\gamma\gamma$ events, after requiring that the transverse momentum-squared be less than $300\,\text{MeV}^2/c^2$. The Monte Carlo is the absolutely normalized QED prediction.

Measurement of $K_L \to e^+e^-\gamma\gamma$



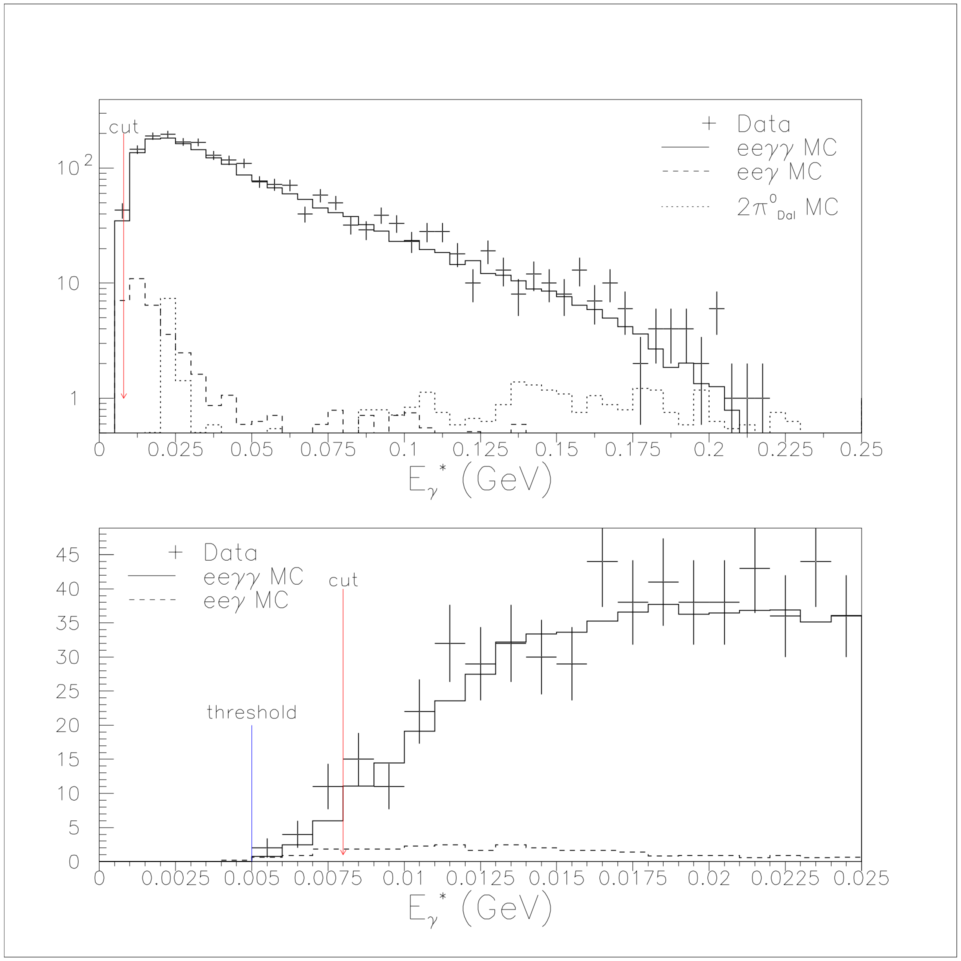
Projected distributions of transverse momentum-squared and Invariant Mass of $e^+e^-\gamma\gamma$ system, showing predicted contributions from $K_L \to e^+e^-\gamma\gamma$ and background processes.

Measurement of $K_L \to e^+e^-\gamma\gamma$



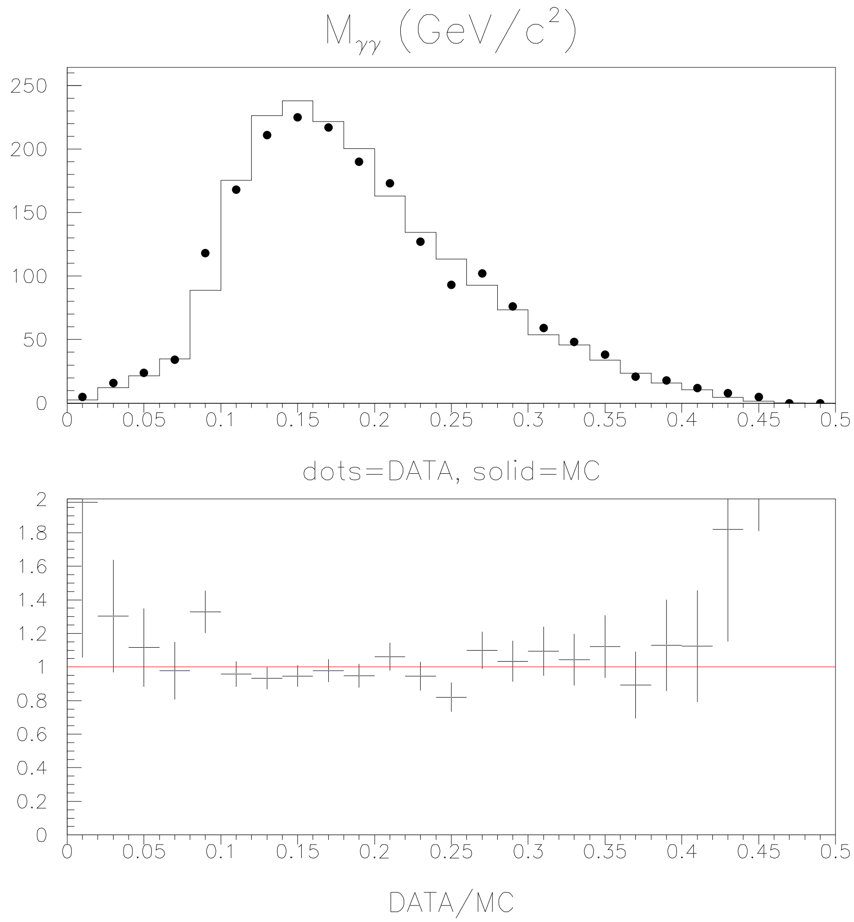
Distribution of the minimum angle between a photon and a lepton momentum vector. The angles for external bremsstrahlung are significantly smaller than for internal bremsstrahlung, allowing separation of this important background to $K_L \to e^+e^-\gamma\gamma$.

Measurement of $K_L \to e^+e^-\gamma\gamma$



Distribution of the minimum center-of-mass photon energy for identified $K_L \to e^+e^-\gamma\gamma$ events, showing predicted contributions from signal and background processed. The quoted branching ratio uses an infrared cutoff of $E^*_\gamma > 5\,\mathrm{MeV}$.

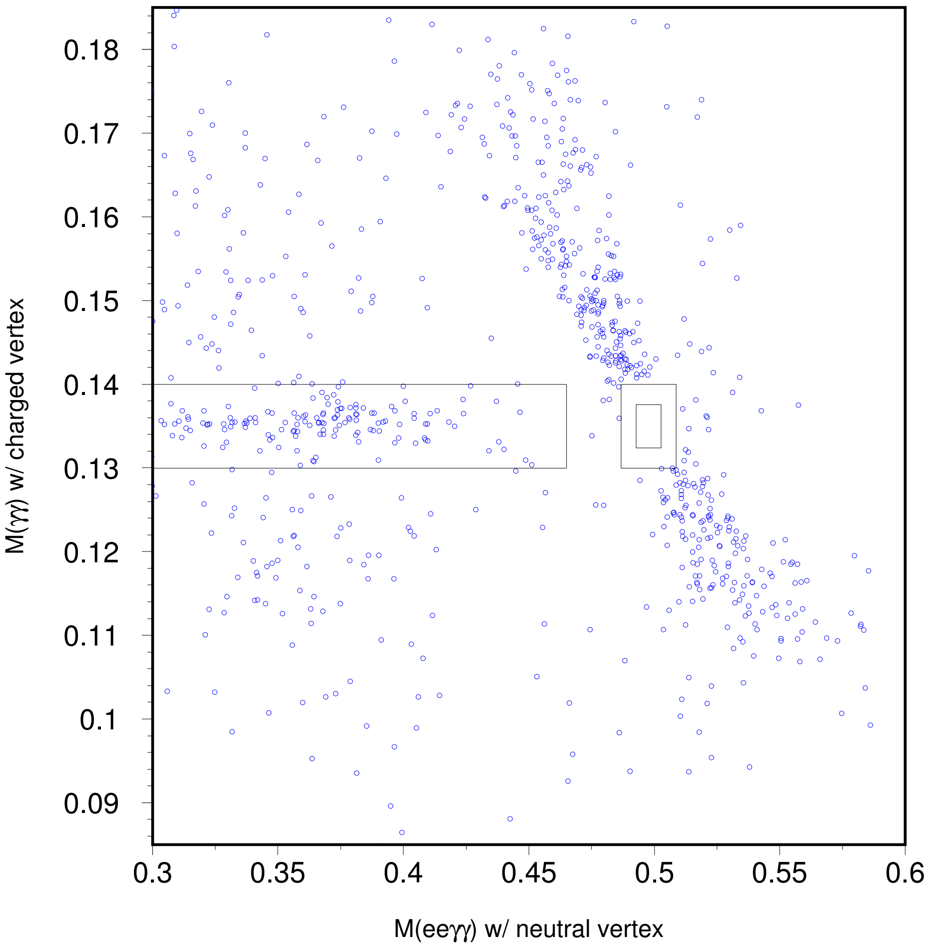
Measurement of $K_L \to e^+e^-\gamma\gamma$



Distribution of $\gamma\gamma$ invariant mass in $K_L \to e^+e^-\gamma\gamma$ events. The observed and predicted distributions agree well.

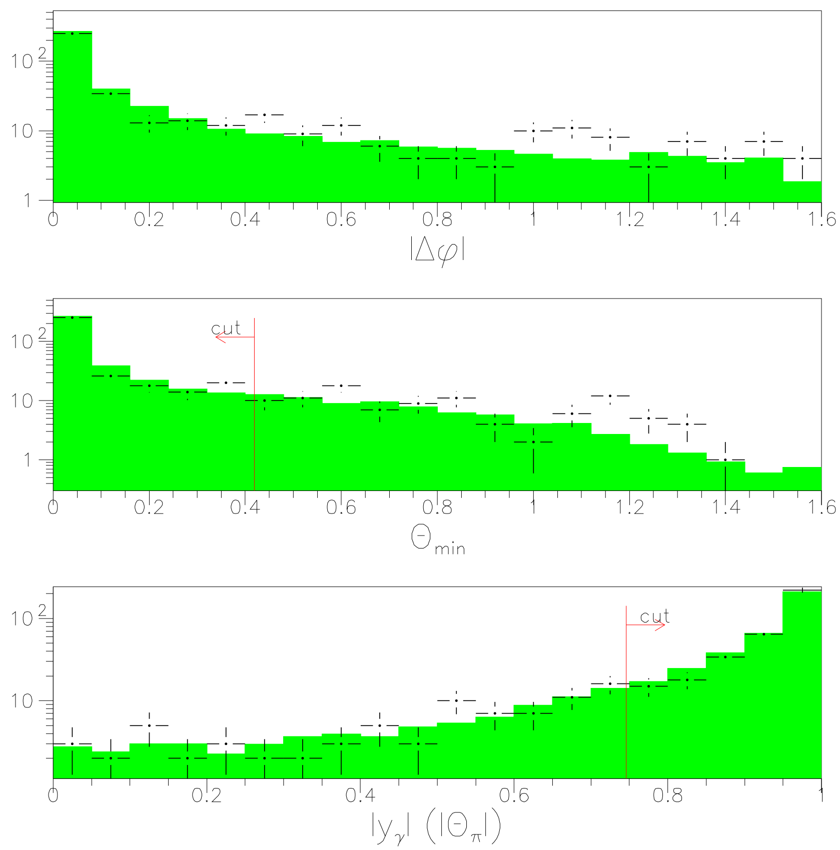
Events with $M(\gamma\gamma)$ near the π^0 mass are possible $\pi^0e^+e^-$ background.

Search for $K_L \to \pi^0 e^+ e^-$



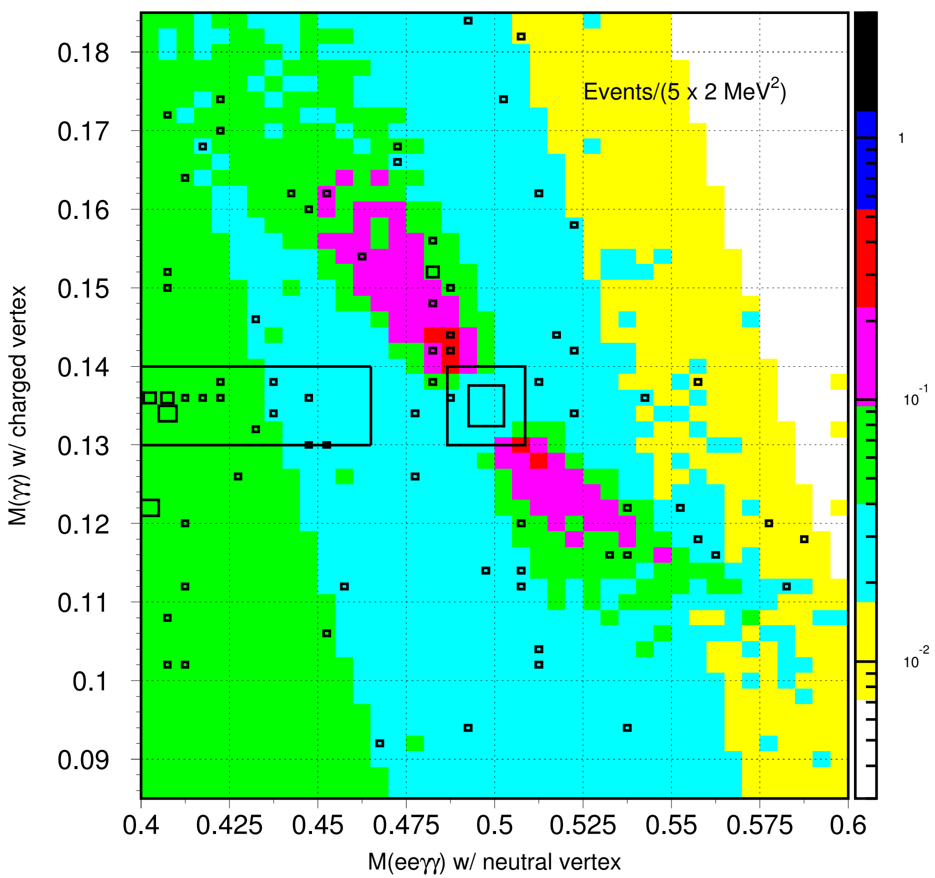
$K_L \to \pi^0 e^+ e^-$ candidate events, before any invariant mass or kinematic cuts have been made. The box in the center is the "blind" region. The long box is populated by $K_L \to \pi^0 \pi^0_D$ events, and the diagonal stripe consists of $K_L \to e^+ e^- \gamma\gamma$ events.

Search for $K_L \to \pi^0 e^+ e^-$



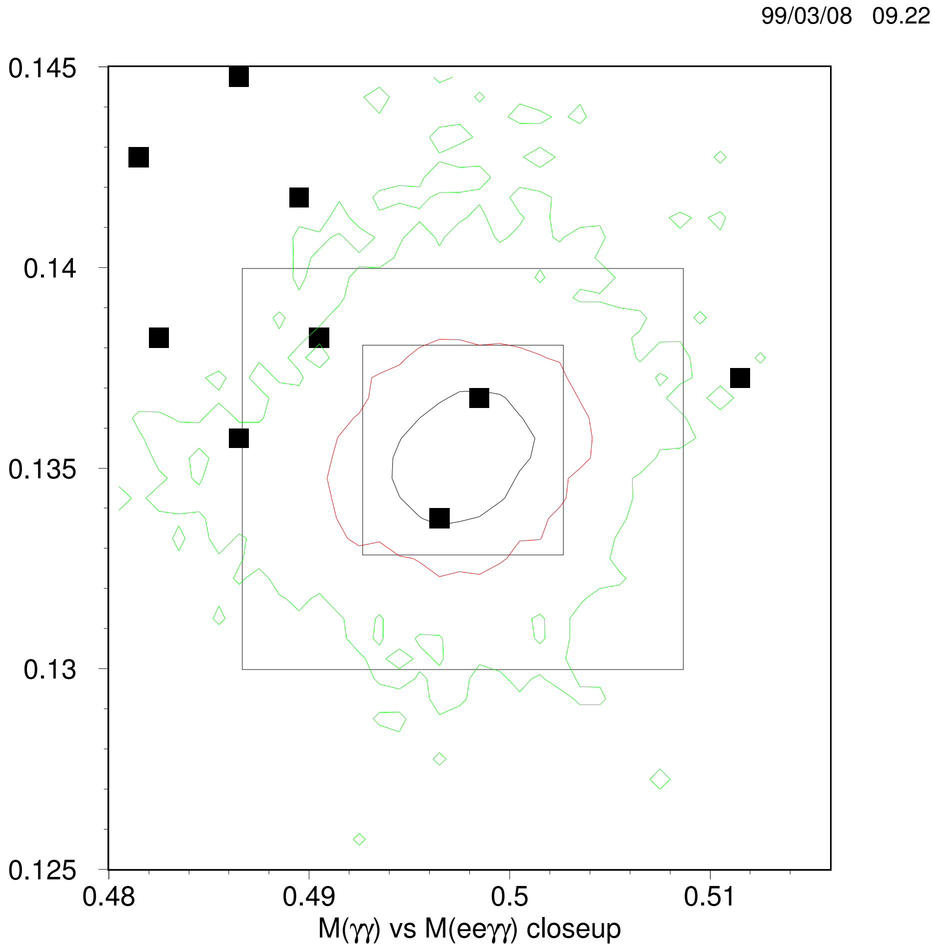
Distributions of kinematic angles for $K_L \to e^+e^-\gamma\gamma$ events outside the signal box. Cuts are made requiring $\cos(\theta_\pi) < 0.746$ and $\theta_{min} > 0.419$ as shown to reduce background from this process to $K_L \to \pi^0 e^+ e^-$.

Search for $K_L \to \pi^0 e^+ e^-$



$K_L \to \pi^0 e^+ e^-$ candidate events, after kinematic cuts requiring $\cos(\theta_\pi) > 0.746$ and $\theta_{min}(e-\gamma) > 0.419$ have been made to remove most $K_L \to e^+ e^- \gamma\gamma$ events. The colored background shows the fitted background level outside the "blind" signal box.

Search for $K_L \to \pi^0 e^+ e^-$



The contents of the now-opened $K_L \to \pi^0 e^+ e^-$ signal box. There are two candidate events, consistent with the expected background of 1.06 ± 0.41 events, primarily from $K_L \to e^+ e^- \gamma\gamma$. The contours should contain 68% (black), 95% (red), and 99.8% (green) of any signal.

$K_L \to e^+e^-\gamma\gamma$ Branching Ratio:

Based on a sample of 1543 events above background, and with an infrared cutoff of 5 MeV photon energy in the K_L rest frame,

$$B(K_L \to e^+e^-\gamma\gamma) = (5.84 \pm 0.15 \pm 0.32) \times 10^{-7}$$

This is in good agreement with previous measurements and the QED prediction.

Search for $K_L \to \pi^0 e^+e^-$:

The single-event sensitivity after all cuts is 1.05×10^{-10}. The expected background, primarily from $K_L \to e^+e^-\gamma\gamma$, is 1.06 ± 0.41 events.

Two events are seen, consistent with background. Based on the expected background level, we set a 90% Confidence Level upper limit:

$$B(K_L \to \pi^0 e^+e^-) < 5.1 \times 10^{-10}$$

This is still about two orders of magnitude from the Standard Model expectation for the direct CPV part.

$K_L \to \pi^0\mu^+\mu^-$ Backgrounds:

Mode	N° Events
$\mu^+\mu^-\gamma\gamma$	0.373 ± 0.048
$\mu^+\mu^-\gamma + \gamma_{ACC}$	<0.023
$\pi^+\pi^-\pi^0$, 2 decays	0.272 ± 0.103
$\pi^+\pi^-\pi^0$, 1 decay, 1 punch	0.007 ± 0.007
$\pi^+\pi^-\pi^0$, 2 punch	0.007 ± 0.007
$\pi^\pm\mu^\mp\nu + 2\gamma_{ACC}$, decay	0.167 ± 0.097
$\pi^\pm\mu^\mp\nu + 2\gamma_{ACC}$, punch	0.063 ± 0.037
$\pi^0\pi^\pm\mu^\mp\nu$, decay	0.010 ± 0.010
$\pi^0\pi^\pm\mu^\mp\nu$, punch	<0.095
Total	1.02 ± 0.18

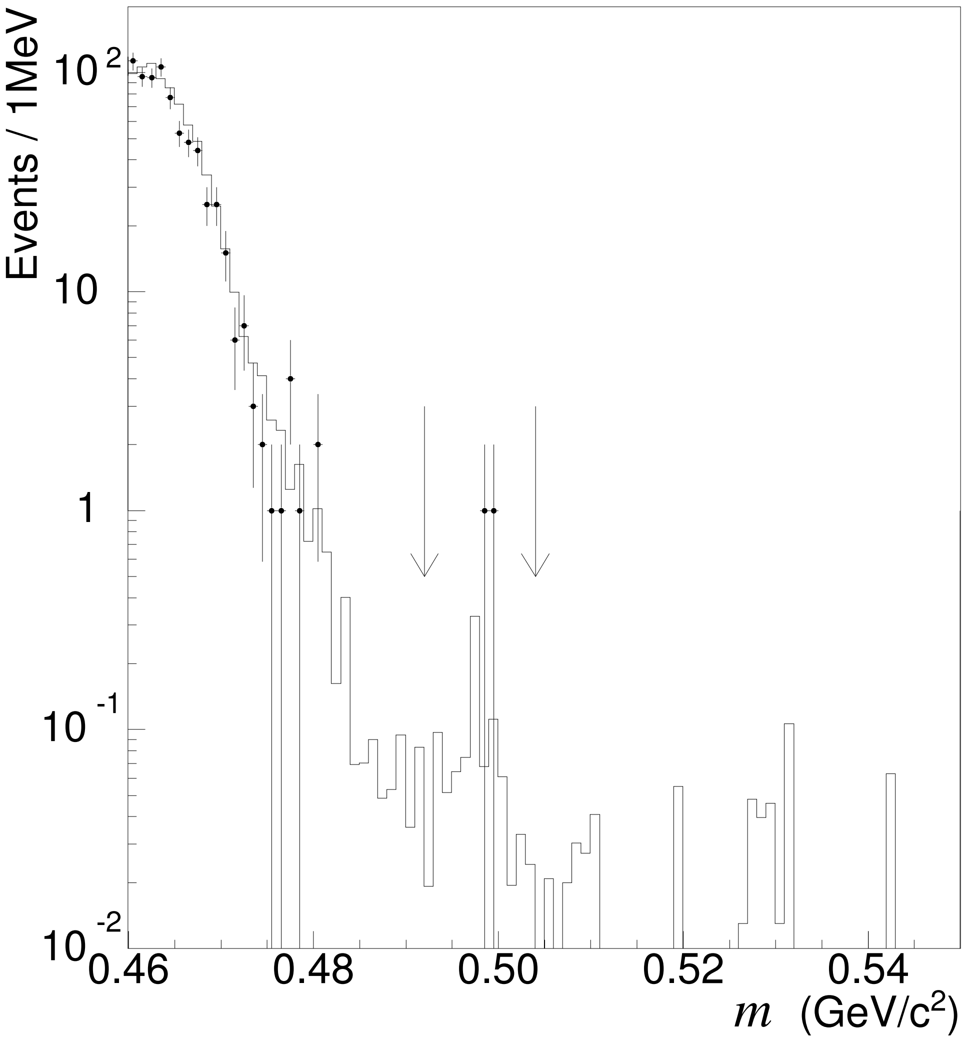
Search for

$$K_L \to \pi^0\mu^+\mu^-$$

Acceptance = $5.40 \pm 0.31\%$
Higher than $e^\pm$ mode because
we dropped all kinematic cuts,
-including $M(l^+l^-) > M(\pi^0)$

S.E.S. = 6.9×10^{-11}

Search for $K_L \to \pi^0\mu^+\mu^-$



The expected background is 0.87 events.

The final KTeV result is

$B(K^0_L \to \pi^0\mu^+\mu^-) < 3.8\times10^{-10}$ (

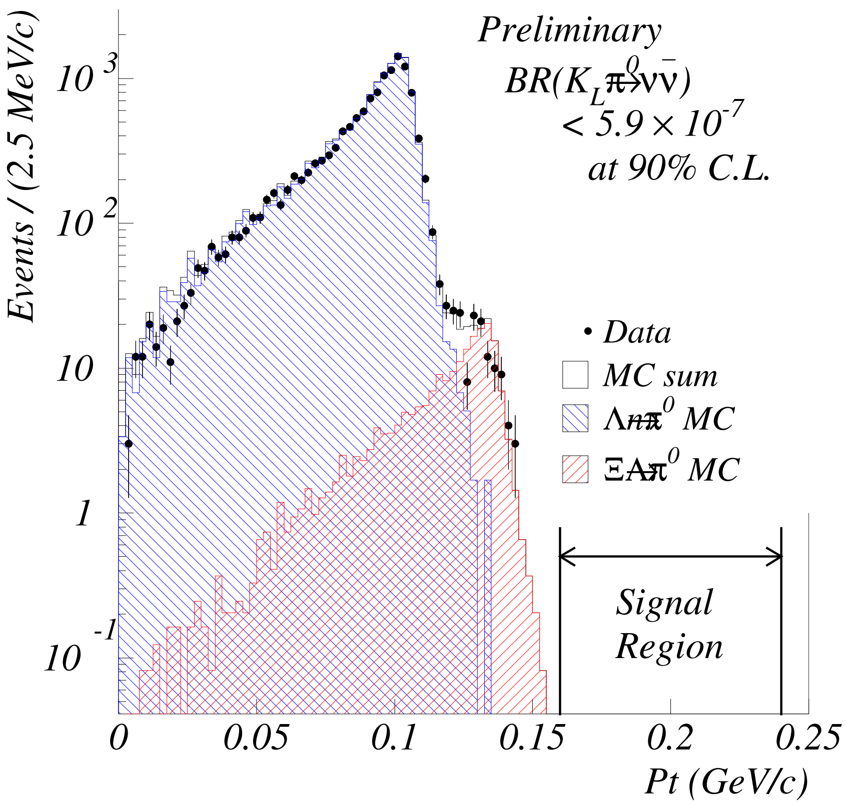
Search for the Decay $K_L \to \pi^0 \nu\bar{\nu}$

The decay $K_L \to \pi^0 \nu\bar{\nu}$ is theoretically a very clean mode: the branching ratio is proportional to η^2_{CKM} and should be between 2 and 4×10^{-11}.

This mode is unfortunately very difficult to detect experimentally, and there are many serious background sources, including $K_L \to \pi^0\pi^0_D$, $\Xi^0 \to \Lambda\pi^0_D$, $\Lambda \to n\pi^0_D$, and n interactions in material.

KTeV has searched for this mode in two ways:

- Using the usual $\pi^0 \to \gamma\gamma$ decay, with a thin "pencil-beam" to fix the transverse decay vertex: we ran in this special configuration for only one day.
- Using the $\pi^0 \to e^+e^-\gamma$ decay to fix the transverse vertex location. The branching ratio for the π^0 Dalitz decay is only 1.2%, but we could use the whole E799 run for this analysis.



Search for the Decay $K_L \to \pi^0 \nu\bar{\nu}$

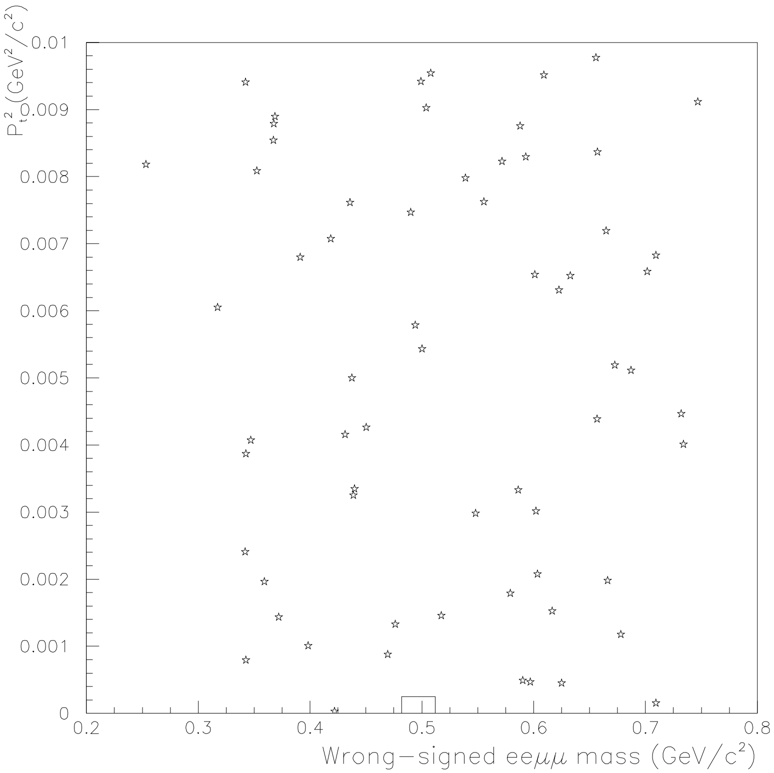
The all-neutral mode had one background event, and the upper limit from that analysis was found to be

$$B(K_L \to \pi^0 \nu\bar{\nu}) < 1.6{\times}10^{-6} \ (90\% \, C.L.)$$

Using the whole E799-II dataset, an analysis based on the π^0 Dalitz decay yields the best limit to date:

$$B(K_L \to \pi^0 \nu\bar{\nu}) < 5.9{\times}10^{-7} \ (90\% \, C.L.)$$

(This corresponds to an upper limit of 52 on η_{CKM}.)



Search for $\Delta L = 2$ Lepton Flavor Violation

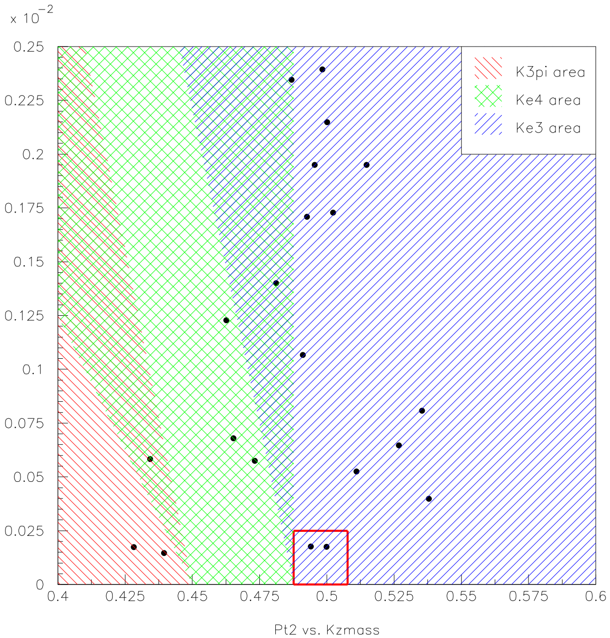
As a byproduct of the measurement of $K_L \to e^+e^-\mu^+\mu^-$, we have search for the lepton-flavor-violating decay $K_L \to e^+e^+\mu^-\mu^-$ and its charge conjugate.

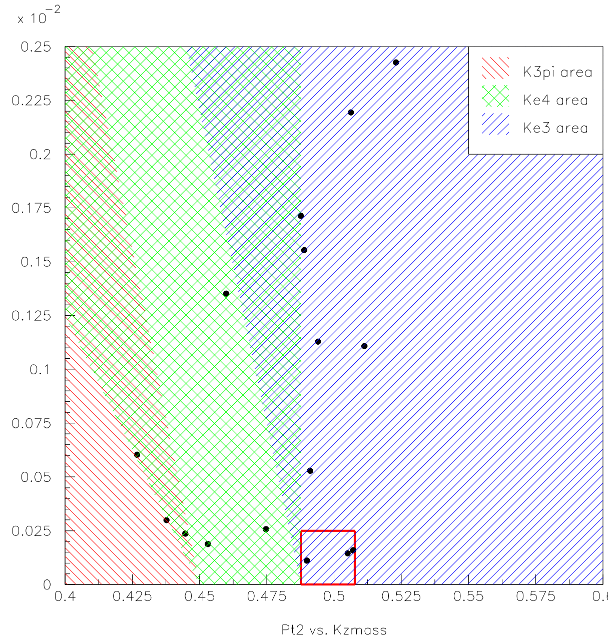
No events are seen in the search region in the $P_\perp^2$ vs $M(\mu\mu ee)$ plane, leading to an upper limit

$$BR(K_L \to e^\pm e^\pm \mu^\mp \mu^\mp) < 4.12 \times 10^{-11}$$

at the 90% confidence level.

Search for $K_L \to \pi^0 \mu^\pm e^\mp$





- KTeV has searched for the lepton-flavor-violating decay mode $K_L \to \pi^0 \mu^\pm e^\mp$. The backgrounds in this search are dominated by semileptonic decays with accidental activity, and have proven difficult to simulate.
- In the 1997 data, 2 events were observed in the signal region, compared to an expected background of about 0.6 events.
- In the 1999 data, 3 events were observed in the signal region, compared to an expected background of about 0.5 events.

Search for $K_L \to \pi^0 \mu^\pm e^\mp$

- $\triangleright$ We believe that the five events are background, albeit one not yet understood or correctly predicted.
- $\triangleright$ We therefore quote a 90% confidence level upper limit, treating these events as though they were a signal:

$$BR(K_L \to \pi^0 \mu^\pm e^\mp) < 3.31 \times 10^{-10}$$

- $\triangleright$ A search for $\pi^0 \to \mu^\pm e^\mp$ using $K_L \to \pi^0 \pi^0 \pi^0$ is also underway. Results have not yet been determined.

Selected E799 Rare Decay Results

Decay Mode	Events	Br. Fraction or 90% CL Limit
$K_L \to \pi^0 e^+ e^-$	2 (bkgd)	$< 5.1 \times 10^{-10}$
$K_L \to \pi^0 \mu^+ \mu^-$	2 (bkgd)	$< 3.8 \times 10^{-10}$
$K_L \to \pi^0 \nu \bar{\nu}$	0	$< 5.9 \times 10^{-7}$
$K_L \to \pi^0 \mu^\pm e^\mp$	2 (bkgd)	$< 4.4 \times 10^{-10}$
$K_L \to \pi^+ \pi^- e^+ e^-$	1508	$(3.63 \pm 0.11 \pm 0.14) \times 10^{-7}$
$K_L \to \pi^0 \pi^0 e^+ e^-$	1 (bkgd)	$< 5.4 \times 10^{-9}$
$K_L \to \pi^0 e^+ e^- \gamma$	48	$(2.34 \pm 0.15 \pm 0.13) \times 10^{-8}$
$K_L \to \mu^+ \mu^- \gamma$	9327	$(3.62 \pm 0.04 \pm 0.08) \times 10^{-7}$
$K_L \to e^+ e^- \mu^+ \mu^-$	133	$(2.69 \pm 0.24 \pm 0.12) \times 10^{-9}$
$K_L \to e^\pm e^\pm \mu^\mp \mu^\mp$	0	$< 1.36 \times 10^{-10}$
$K_L \to e^+ e^- e^+ e^-$	1056	$(4.16 \pm 0.13 \pm 0.21) \times 10^{-8}$
$K_L \to e^+ e^- \gamma \gamma$	1543	$(5.84 \pm 0.15 \pm 0.32) \times 10^{-7}$
$K_L \to \mu^+ \mu^- \gamma \gamma$	4	$(10.4^{+7.5}_{-5.9} \pm 0.7) \times 10^{-9}$

KTeV Summary and Prospects

- The rare decay experiment E799 has observed or set limits on numerous K_L decays. Most analyses of 1997 data are now published. Results from 1999-2000 are still to come.

- Searches for rare K decays have limited bsome eyond-the-Standard Model theories, but many searches have now reached the level of tough backgrounds.

- The rare decays $K_L \to \pi^0 e^+ e^-$ and $K_L \to \pi^0 \mu^+ \mu^-$ are limited by radiative Dalitz backgrounds. Even if that could be overcome, the presence of long-distance amplitudes complicates the interpretation of any measurement.

- Much progress has been made on understanding “medium-rare” K_L decays.

- Future rare decay experiments in the kaon sector will focus on the theoretically-clean, but experimentally challenging decays $K \to \pi \nu \bar{\nu}$.

Does rare K-Decay physics have a future?

- A follow-on experiment to NA48 called NA48/1 at CERN will study K_S decays, while a second phase, NA48/2 will make precision measurements of $K^{\pm}$ decays.

- The search for the neutral "golden mode" $K_L \to \pi^0 \nu \bar{\nu}$ will carry on via E391a at KEK, now taking data, and a dedicated JHF experiment being planned.

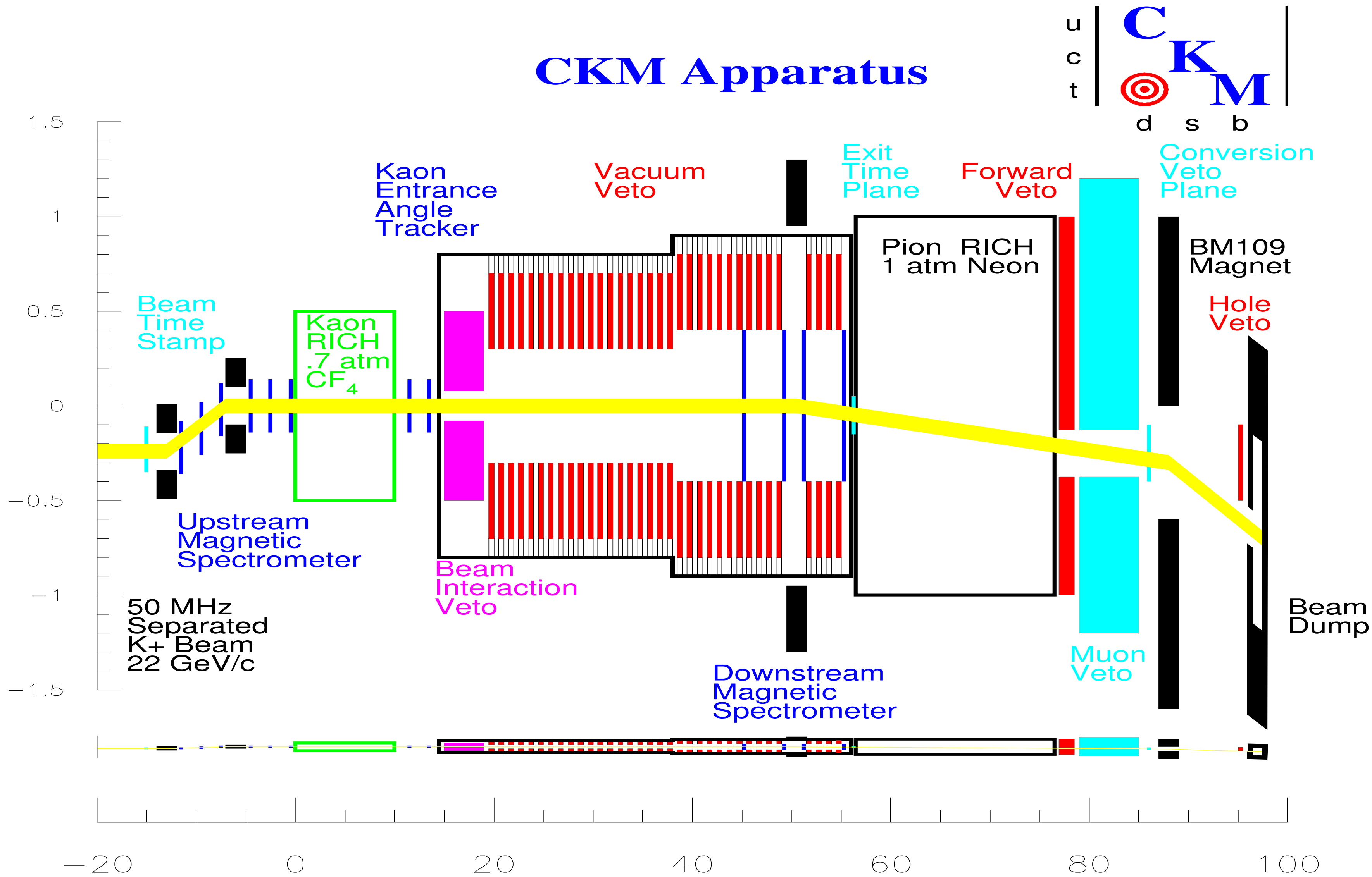
- If NSF/MRE funding can be secured, KOPIO at Brookhaven will also search for $K_L \to \pi^0 \nu \bar{\nu}$ as part of the RSVP Initiative (Rare and Symmetry-Violating Processes).

- The proposed CKM experiment at Fermilab hopes to make a 10% measurement of the charged "golden mode" $K^+ \to \pi^+ \nu \bar{\nu}$

So what about CKM?

- The CKM project aims to observe about 100 events of the rare decay $K^+ \to \pi^+ \nu\bar{\nu}$. This should permit a 10% measurement of $|V_{td}|$ in the CKM matrix, and allow precise comparisions between measurements in the K and B sectors.
- The branching fraction for this mode can be reliably related to CKM matrix parameters in the Standard Model. The expected branching fraction is about 1×10^{-10}.
- A single-event sensitivity of 10^{-12} will be required. This is about a factor 50 improvement over KTeV/E799.
- CKM has learned a lot about how to do this measurement from the experience of E787 and E949 at Brookhaven; E787 has already seen two clean events in this mode.
- CKM will use an RF-separated beam of 22 GeV K^+ with about 5 MHz of decays in the 30-meter-long fiducial volume.

CKM Apparatus



CKM Detector Features

- The key feature of the detector, based on E787/E949 experience, is **redundancy**. RICH detectors act as velocity spectrometers to complement magnetic spectrometers. Pions can be identified by E/P as well as by the pion RICH combined with the downstream straw chambers.

- Veto coverage is much more extensive than in KTeV, and must maintain efficiency at lower energies. This is required to control the $K^+ \to \pi^+\pi^0$ background.

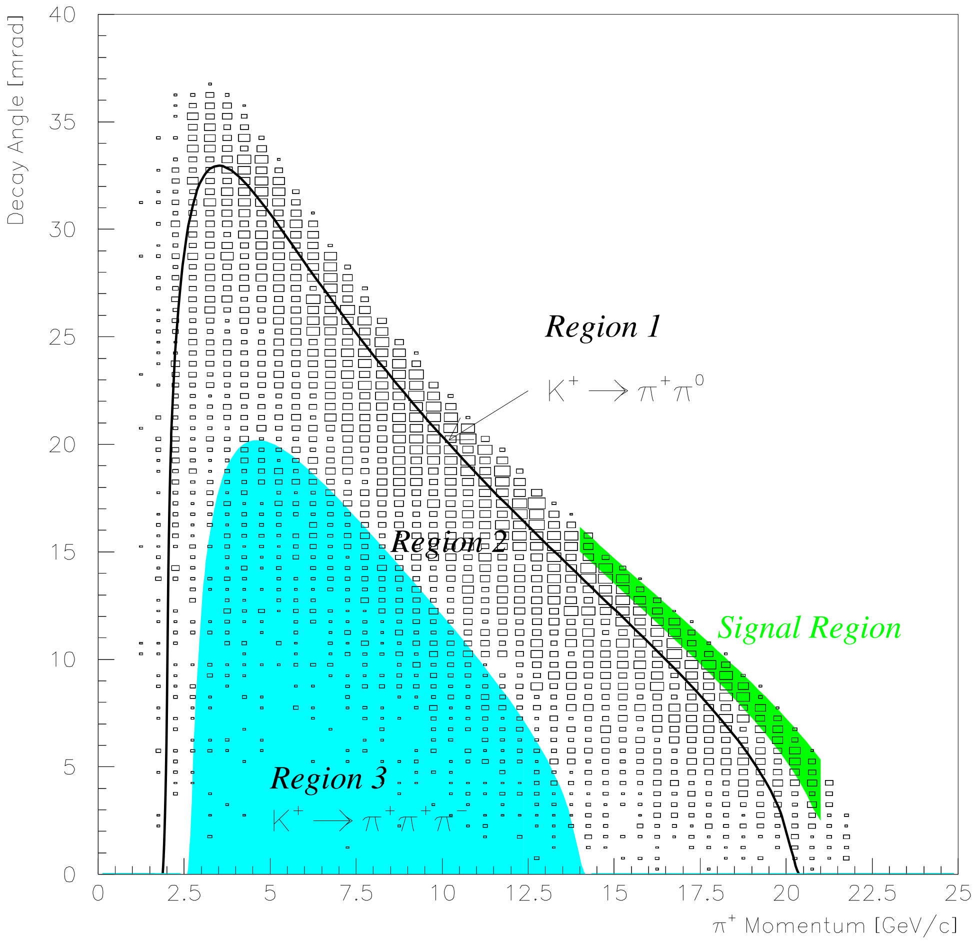
- CKM will inherit the KTeV CsI for use as the "Forward Veto System." The KTeV magnet and some other KTeV detectors will also be reused.

- The spectrometer is a **general-purpose** detector, albeit optimized for detecting $K^+ \to \pi^+\nu\bar{\nu}$ and controlling backgrounds. Many K^+ decay modes can be accurately measured.

More CKM Detector Features

- ▷ The CKM beam will be debunched to minimize accidental pileup while maintaining high intensity.
- ▷ To minimize scattering interactions, the CKM straw chambers will be installed in the vacuum decay volume.
- ▷ CKM plans to use a no-hardware-trigger DAQ based on a Gigabit ethernet network switch and a PC farm.
- ▷ A longitudinal stack of scintillator tiles in the vacuum veto system will be read out by multiple, independent PMT's to ensure that no photon will be missed due to transient PMT or HV failures.

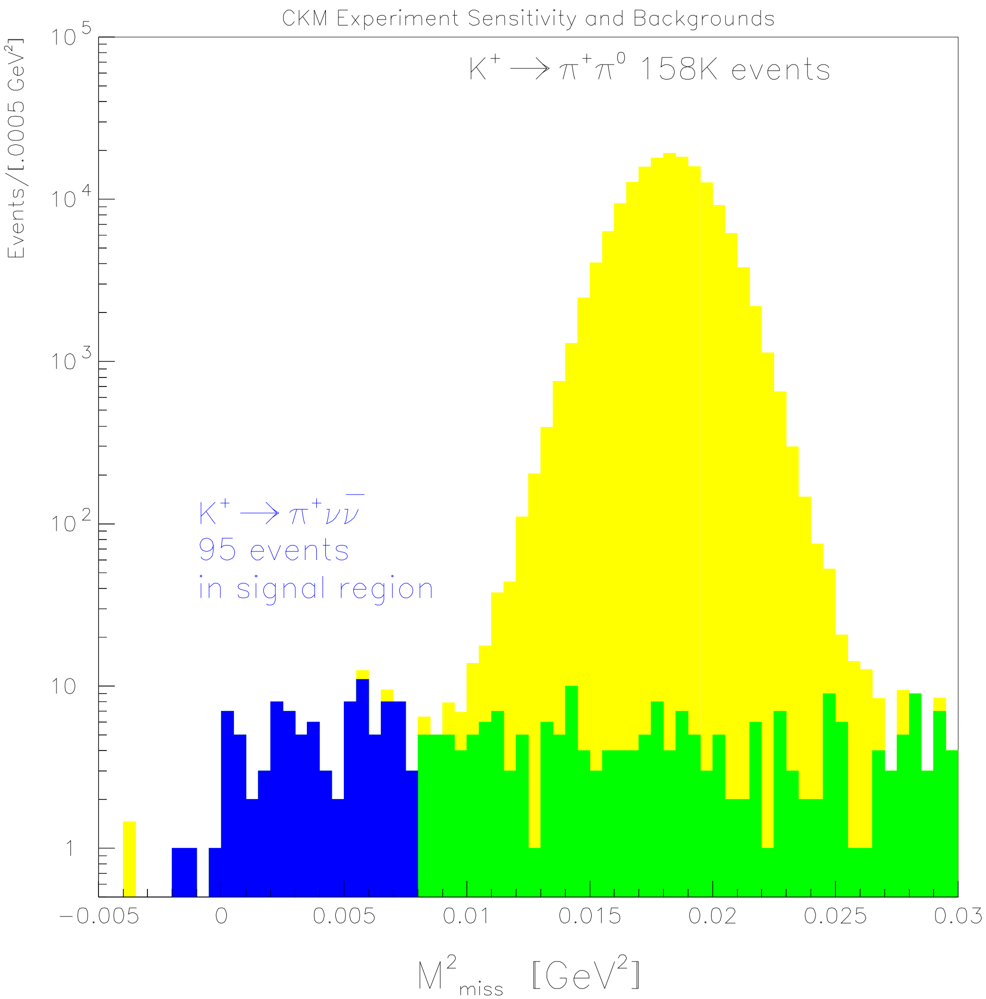
Finding the Signal for $K_L \to \pi^+\nu\bar{\nu}$



For the $\pi^+\nu\bar{\nu}$ measurement, only that part of phase space where the pion momentum is greater than 14 GeV/c will be used because this threshold is necessary to ensure that beam kaons don't leave rings in the pion RICH.

The decay angle must be at least 2.5 mrad to ensure sufficient decay-vertex resolution.

Finding the Signal for $K_L \to \pi^+\nu\bar{\nu}$



After these (and other) cuts, a missing mass cut is used to reject the remaining $K^+ \to \pi^+\pi^0$ background, as shown here.

This plot is what is expected after two years of running.

Yes, but will CKM happen?

- The experiment received Stage I approval from FNAL in June 2001 (based on the review on which the KAMI $K_L \to \pi^0 \nu \bar{\nu}$ proposal was killed)
- Under current accounting procedures, CKM is estimated to cost around \$ 100 million, including contingency, G&A, etc etc.
- CKM is among the possible future projects being reviewed by the P5 Subpanel of HEPAP; their initial report is expected shortly.
- The CKM Collaboration is preparing a technical design report and WBS in the hope that the project will be baselined with a Lehman Review in early 2004.
- Tentative FNAL long-range plans call for CKM running in 2009-10. (long timescales not being limited to the Energy Frontier, after all.)